THE COMPLETE GUIDE TO

Restoring Your Soil

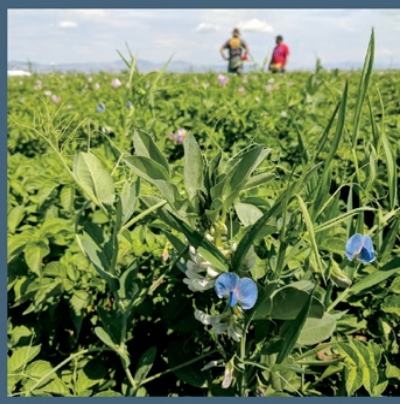
DALE STRICKLER

Author of *Managing Pasture* and *The Drought-Resilient Farm*

IMPROVE water retention and infiltration

SUPPORT microorganisms and other soil life

CAPTURE more sunlight



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To my children, Cole and Cassie, my two greatest creations

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Farm Smarter with More Books by Dale Strickler

Share Your Experience!

PREFACE

By the Skin of Our Earth

Once, in college, an acquaintance heard me talking about my Soils class. She looked at me, rather puzzled, and asked, "You mean they have a whole class on *dirt*?"

As it turns out, there's more to know about dirt than most people realize, including yours truly. When I set out to write this book, I thought I would create the final, authoritative, definitive reference to turning degraded, lifeless dirt into rich, productive soil. After all, I had a couple of degrees in agronomy and had worked with soils all my life, and I thought I knew a little something about the topic.

It wasn't long before that task appeared overwhelmingly large. In my research and reading, I found that there are entire books written about each chapter of this book; in fact, there are entire books written about each sentence in some of these chapters.

For example, in the chapter on carbon-based soil amendments, biochar gets just a brief discussion, but there are huge textbooks written about biochar alone, and there are scientists who specialize in that one topic and write scientific papers I can barely decipher. The same could be written about aerobic composting, or anaerobic composting, or manure—all of which are merely parts of one chapter in this book. How in the world could I condense all the knowledge of all those scientific books into one volume?

I also began to feel a bit intellectually challenged. Each of those authors knew far more about their topic than I, obviously, and it would take years of research and investigation on every single element to become sufficiently qualified to write the book I had originally planned. If I were to write that book, it would not be a book; it would have to be volumes of books, and I would not finish them in a single lifetime.

So, midstream, I decided to change my goal from writing the *last* book on soil restoration to writing the *first* book on soil restoration that an ordinary person would actually want to read.

My goal now with this book is to offer a starting point from which people can branch out and dig deeper into whichever topics pique their interest the most, and to provide the background and resources to do so. Much of this book will sound like a broken record (for those old enough to remember broken records). The same themes will recur throughout this book. It is not repetition, it is reinforcement.

—Dale Strickler

PART I

Why Restore Soil?

"Man, for all his artistic pretensions, his sophistication, and his many accomplishments, owes his existence to a six-inch layer of topsoil and the fact that it rains," wrote radio commentator Paul Harvey. While those words are quite true, it is also alarming that the precious six-inch layer of topsoil he mentions is all too rapidly becoming less than six inches, and the remaining inches are becoming less productive. Meanwhile, the population of humans that depend on this thin layer for survival is increasing every day.

These two trends seem destined someday to result in quite tragic consequences unless one or both of two drastic measures are taken. One would be the ugly business of human depopulation; the other would be the restoration of our planet's soils to a more productive and protected state. Which sounds more appealing?

01

Soil Salvation

During my teen years growing up on the farm, my father one day sent me to till a far-off piece of land, prior to planting. His instruction was that if the soil was too wet I should turn around and come back and we would wait for better conditions. I got there, and it was too wet. I didn't want to make another long, boring tractor trip, so I tilled it anyway.

> The next night he called my brother and me in to see him. “Boys,” he said, “it has become apparent that one of you is smarter than the other.” He looked at me and said, “Dale, that’s why you are going to go to college. ” He then turned to my brother. “Jeff, you are going to stay here and farm.”

He held out his hand, and in it was a piece of soil from the field I had tilled too wet. It had baked rock-hard in the sun. He hit it once, twice, three times with a ball-peen hammer, and it broke only on the third hit. Then he looked at me again and said, “Dale, you aren’t smart enough to make a living farming this soil,” and left the room. (He actually used a different word than “soil.”)

Our farm had been cursed with some of the worst soil imaginable for cropping. The extremely heavy clay soils of Southeast Kansas were much better suited to making bricks (and in fact, brick- making was an industry in our area). One hundred years of tillage had robbed our land of most of the organic matter and topsoil that had developed during the previous 10,000 years. Although this same tillage and erosion had taken place over most of the United States, the loss of topsoil and organic matter was especially disastrous on our thin claypan soils that had precious little of these assets to begin with.

My father’s words that day were very true. I was a tremendously aggravating farmhand, and my inattentiveness (ADHD, as I was to learn much later) must have been incredibly

frustrating. It may seem as though my father was just being mean, but he was also being honest. I wasn't smart enough to manage that soil.

My Education in Soil

My personal goal at college was to learn how to make soil better. I discovered that the key was to raise the soil organic matter, which certainly seemed simple enough. However, I was taught in my Soils class that it is virtually impossible to raise soil organic matter content on a widespread scale on a permanent basis.

This information was not encouraging, and I could not accept it for an answer. There had to be a way. I continued my education, completing both a bachelor's degree and master's degree in agronomy. And yet, after all those years of education, the solution remained elusive.

Garden books were far more encouraging than my Soils professors, though ultimately no more useful. Their solution was simply to add a 6-inch layer of lawn clippings to the soil. Easy enough for a 1,000-square-foot garden: You just take the lawn clippings from a dozen 1,000-square-foot lawns. But what about a 1,000-acre farm? It would take 12,000 acres of lawns to provide enough clippings. And what of the lawns that are being robbed of their organic matter in order to enrich the garden?

Garden books were far more encouraging than my Soils professors, though ultimately no more useful. Their solution was simply to add a 6-inch layer of lawn clippings to the soil.

To increase soil organic matter in this way on the entire planet, where are we going to find 12 other Earths, and how are we going to transport all of their organic matter back to our Earth?

Seeking Solutions

Most garden recommendations on improving soil involve stealing organic matter from one piece of land to enrich another. But is this a useful practice on a farm scale, let alone a planetary scale? To increase soil organic matter in this way on the entire planet, where are we going to find 12 other Earths, and how are we going to transport all of their organic matter back to our Earth?

The answers I sought were not easy to find in books. Instead, I made connections with like-minded people, and we discussed our ideas. I plucked ideas from organic farmers, who had developed methods of providing fertility without the easy crutch of a fertilizer bag. I gleaned ideas from no-till farmers, who had developed systems to avoid the soil destruction associated with tillage. I found that many people had valuable ideas, but no one seemed to have the entire solution.

Developing this solution became my goal. Along the way I developed my own ideas and theories, but the final piece of the puzzle was to put them into practice. So I bought my own farm and set my plans into motion.

Over the past 15 years I have done what my professors taught me was impossible. My soil organic matter has nearly doubled in that short time span. Where I could not find a single earthworm 15 years ago I can now pluck dozens from a single shovelful.

Perhaps most important, this transformation did not require economic sacrifice. On the contrary, the process has been more profitable than if I had farmed "normally," and it becomes more profitable every year. No matter how noble the goal, if it cannot be achieved profitably, it will not be achieved at all, because it will not even be attempted.

Restoring Habitat, One Field at a Time

On my own farm, I replaced a sterile corn–soybean field with a diverse pasture blend of grasses, legumes, and forbs, harvested by cattle. But cattle are not the only animals on this field.

One summer day, while the field was still in that corn–soybean rotation, I took my son insect-collecting on the soybean field. We found a total of five species of insects (all considered pests). We saw no mammals, birds, reptiles, or amphibians. The field had one species of plant, thanks largely to my efforts at hand-hoeing any weeds that escaped the sprayer and tillage equipment.

Now, in that same field, since planted to a complex polyculture of perennial forages, I have dozens of species of plants, from multiple plant families, and mushrooms sprouting below the plants. I can now count dozens of insect species. Toads, tree frogs, snakes, lizards, meadow voles, foxes, rabbits, weasels, and who knows what other animals scurry ahead of me unseen, while orioles, cowbirds, cattle egrets, little brown bats, and swallows swoop overhead after the insects.

What has happened on my farm, however, is the exception to the current trend. More often, the opposite occurs: Every year more prairies are plowed and planted to crops, while ruminant livestock are fed grain. Tillage, fallow, removal of biology from soil and livestock from land: All these contribute to a deepening, and dangerous, impoverishment of our soil.

The Planet Needs Better Soil

Along the way in my search for knowledge, I learned that the process of building soil could do far more than simply make my own little piece of the earth more profitable. I learned that the root causes of many of society's miseries can be traced directly or indirectly to soil misuse.

To understand why this is so, you must first understand a fact that is little known outside of the agriculture profession:

> **Tillage increases crop production because it destroys soil organic matter, breaking it down into carbon**

dioxide and the mineral elements of soil fertility: nitrogen, phosphorus, etc.

Tillage works like a bank withdrawal from a savings account. It allows you to convert what is normally a slow release of nutrients into a rapid flush of nutrients, but it does not actually create nutrients. And if repeated often enough, after a surprisingly short time period the organic matter savings account is gone.

Consider the History

Every great civilization in history has followed the same path. First it develops an extractive method of agriculture, based on tillage and annual crops, that converts stored soil wealth into surplus food. This allows an advanced society to develop, as people are freed from their role as hunter-gatherers and can focus on other pursuits. This is short-lived, however, since a soil-depleting agriculture can sustain this food surplus for only a short time period before the onset of soil collapse and ruin.

At this point, the civilization feels the need to conquer new lands to maintain its standard of living. It forms armies and wages wars to bring new lands under cultivation and import food from distant shores. Since healthful foods such as meat, fruits, and vegetables do not travel well, the diet shifts to grains, which are nutrient poor (but rich in calories) but travel and store well. Thus, the population becomes malnourished

and prone to illness. Famine, war, and pestilence are all consequences of soil degradation.

With the advent of the machinery age, soil exhaustion could take place at an alarming rate, as evidenced by the Dust Bowl in the Great Plains region of the United States. This rapid soil destruction introduced a new potential menace. Intensive tillage with fossil-fuel-powered machinery depletes the soil carbon stores of the earth, burning two ways simultaneously—by oxidizing soil organic matter with the tillage and by burning petroleum.

The rapid increase in fossil fuel use, coupled with the decline in worldwide soil organic matter, has contributed to atmospheric carbon dioxide levels increasing to nearly double what they were in preindustrial days.

By the Skin of Our Earth

Many believe this is increasing global temperatures and shifting climatic patterns. Much of the political focus is on fossil-fuel use, but the gorilla in the room that no one sees is soil organic matter loss. Many of the proposed solutions to climate change are nothing more than efforts to grab power over land use, or transfer wealth and power into the hands of politicians while doing little or nothing to forestall climate change.

These “solutions” will likely do little or nothing to reduce the threat of climate change. It doesn’t matter if climate change is real or not, or if it is manmade or not. That’s because the wise solution to preventing climate change is also the

solution to world hunger, the solution to war, the solution to disease. In other words, it is a solution we should be pursuing anyway.

That solution is to restore the soils of our planet. In this book lies the blueprint for doing just that.

02

How We Made a Mess of This Planet
and How Soil Restoration Can Save It

On Interstate 70 going through my home state of Kansas you can see a billboard that reads, “A Kansas Farmer Feeds 155 people plus YOU,” touting the ability of a modern farmer to produce enough food to “feed the world.” It is an impressive statistic, and modern agriculture is indeed quite amazing in its productivity. But that success comes at a cost we are only beginning to comprehend.

King Corn

For an example of modern farming’s remarkable productivity, one need only look at what has happened to US corn yields over time, as pictured in the graph below. Note that corn yields were rather stagnant for the first 70 years represented in the graph. The first rapid rise in corn yields came after hybrid varieties became popular, beginning in the late 1930s.

Another uptick in yield began in the 1950s, when wartime technology was put to use for peaceful postwar purposes. Cheap nitrogen fertilizer from the Haber-Bosch process, the insecticide DDT, and the herbicide 2,4-D were all the beginnings of a modern age of agriculture, when technology replaced farming methods that had been in existence for millennia. Fertilizers made plants grow and yield more, herbicides such as 2,4-D and atrazine eliminated weeds that competed with the crops, and DDT killed the insects that were eating them.

The trend in yield increase continues, as literally every day doers and thinkers bring forth new discoveries and techniques to increase productivity. For example:

Farm machinery now contains global positioning units that receive signals from satellites, allowing:

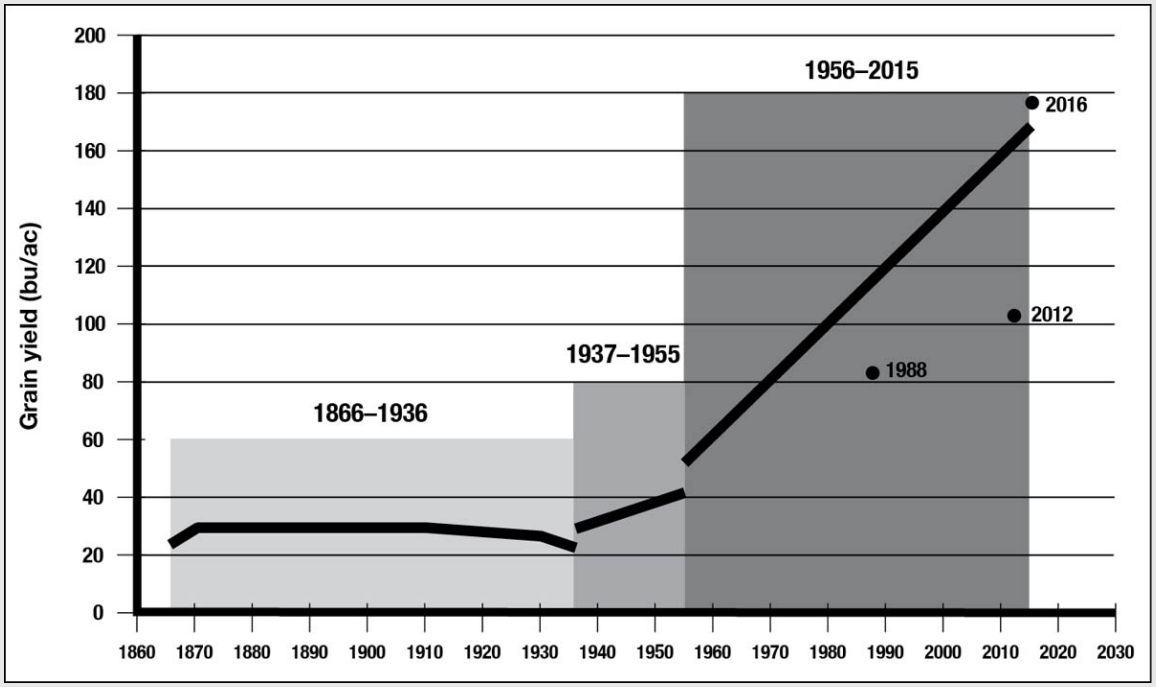
- precision sowing of seed so each plant is spaced precisely the same distance from all other plants
- precision application of herbicides and pesticides to prevent skips and overlaps
- selective application of fertilizers within the fields, based on grid-sampled soil tests.

Genetically modified hybrids now contain a gene from a soil bacterium that makes the plant toxic to corn borer caterpillars and the larvae of the rootworm beetle, historically the two most damaging insects in US corn production.

Supercomputers help us map and identify beneficial genes in corn. That lets us target plant breeding to produce plants that contain certain beneficial genes and not other genes that diminish yield.

As a result, an acre of corn today now averages about seven times the yield of the same acre of corn a hundred years ago.

US Corn Grain Yield Trends since 1866



Source: Adapted and simplified from USDA-NASS data source, January 2017

The Costs of Increased Production

There is no argument that with modern technology we can produce considerably more food per acre than we could a hundred years ago. And given that the primary goal of agriculture is to feed people, it is clear that we have

accomplished this in amazing fashion. But let's take a hard look at some of the effects modern farming systems have had on our soil, our bank balances, our health, our economy, our climate, and our way of life.

Soil Erosion

Probably the most dangerous consequence of agriculture is the loss of the soil itself, from washing or blowing away. I don't think it is an exaggeration to state that soil erosion is the gravest threat to human existence as we know it. (See Figure 1.3.)

This is not a recent problem; it has been occurring since the practice of tillage began several thousand years ago. Tillage was once necessary for the cultivation of annual grain crops. The destructive nature of tillage has been recognized for almost as long as the practice itself, and the results are devastating. In fact, hundreds if not thousands of civilizations throughout history have collapsed due to soil erosion (see Soil Erosion: Further Reading, below).

Loss of Soil Organic Matter

Tillage often results in soil loss on sloping land; however, the practice has been considered rather benign on level land, where soil erosion is not a significant hazard.

Soil Erosion: Further Reading

A couple of excellent works discuss the topic of civilizations throughout history being destroyed by soil erosion. The first is “Conquest of the Land through 7,000 Years,” a report by W. C. Lowdermilk for the US Soil Conservation Service on his world tour examining the effects of agriculture upon the land. It is fascinating and informative and, simultaneously, depressing and grim. I believe it should be required reading for every high school student around the world, and it’s brief and easy enough to read at a leisurely pace in an evening.

Perusing this document should precede anyone’s study into regenerative agriculture. And it is priced right, as it is free to download from the US Department of Agriculture Natural Resources and Conservation Service (visit www.nrcs.usda.gov).

The second work I recommend on this topic is David Montgomery’s *Dirt: The Erosion of Civilizations*, which describes how soil erosion caused the collapse of most of the world’s ancient civilizations. What is particularly sobering is that throughout 6,900 years of the 7,000 years of agricultural history, this ancient soil erosion was caused by hand tools and simple plows pulled by animals. Today, massive tillage equipment pulled by giant tractors is capable of exposing inestimably larger amounts of soil to catastrophic erosion in just a few hours.

Fortunately, for the first time in recorded history we have the technology to farm in a manner that does not destroy the soil on which civilization depends. Unfortunately, however, these methods are in use on only a small fraction of the world's farmland. You would think that methods of farming that have been shown to preserve the primary instrument of maintaining human life on Earth (the soil) would be universally adopted. But they aren't.

It is estimated that the plowing of North American prairies and forests into cropland over the last 500 years has added as much CO_2 into the atmosphere as all the burning of fossil fuels since the advent of the Industrial Revolution across the world.

It is not benign. Tillage results in a loss of soil organic matter due to oxidation. Soils with a history of tillage often have a mere fraction of the organic matter that the soil had when it was still in native vegetation.

In my home state of Kansas, it is a simple matter to see just how much organic matter has been lost in less than a century and a half of tillage. Just take a soil test from a native grass pasture and a cropped field on opposite sides of a barbed wire fence. Cropland in this area ranges from 1 to 2 percent organic matter, while native grass pastures (which are areas that were

considered to have soil that was too poor to plow) range from 4 to 7 percent organic matter.

In other words, our cropping practices caused the loss of somewhere between 50 and 75 percent of the organic matter that was formerly in the soil. When the organic matter is lost, the soil loses its ability to transmit air and rainwater into the soil. As a result, it loses much of its ability to hold water and to supply mineral nutrients to plants.

I have not traveled extensively to countries outside the US, but on my way-too-brief visit to Eastern Europe I was shocked at how much land was still moldboard-plowed annually. On the other hand, I was not shocked to find this soil almost devoid of organic matter after thousands of years of tillage.

Contribution of Carbon Dioxide to the Atmosphere

Fossil fuel use may be the most notorious culprit in raising atmospheric carbon dioxide levels around the globe, but soil tillage is also responsible. When the carbon in the soil organic matter is oxidized by tillage, it goes into the atmosphere as CO_2.

It is estimated that the plowing of North American prairies and forests into cropland over the last 500 years has added as much CO_2 into the atmosphere as all the burning of fossil fuels since the advent of the Industrial Revolution across the world.

THE GOOD NEWS

Although these estimates are sobering to farmers, there is reason for hope and optimism. Consider again the previous statement, that in the last 500 years the loss of soil organic matter in North America equaled the worldwide amount of atmospheric CO_2 emitted by fossil fuels. Now imagine green plants pulling that CO_2 out of the atmosphere through photosynthesis and putting it back into the fields of North America as organic matter, restoring that organic matter to historic levels.

Doesn't it then follow that the level of CO_2 in the atmosphere would drop halfway back to where it was a few hundred years ago? And if that same restoration of soil organic matter were to occur on the rest of the world's cropland, that we could reverse the contribution of CO_2 from all sources during that period?

Thinking Globally

The cropland in North America is only about 15 percent of the world's total. That means that there is seven times more potential in all the world's cropland for carbon sequestration than there is in North America alone. If we could adopt the principles in this book on a worldwide scale, it is quite realistic that we could totally reverse the rise in global CO_2 and return it back to levels that occurred in the preindustrial era.

The best part about adopting the principles in this book, and restoring all of the soil organic matter lost over the last 7,000 years, is that doing so will not require a sacrifice in our lifestyles or economic hardship for the world's poor. On the contrary, it will make food more abundant, available, and

nutritious, with lower input costs required to grow it. It will usher in a new level of prosperity among the world's subsistence farmers.

A Broken Water Cycle

As I write this, Kansas is experiencing some of the worst flooding in state history, rivaling the famous floods of 1951, which spurred construction of several large flood-control projects across the state, including several large flood-control reservoirs and hundreds of smaller watershed ones. A year ago many of these same areas, including my home county, experienced the driest 13-month period in recorded history. What broke that drought in my locale? An 8-inch rain that fell in less than two hours.

I had all my year's calf crop in a creek-bottom pasture, a week away from going to sale. They all were swept away and scattered throughout approximately 4 square miles of 6-foot-tall corn. A couple of them were killed, and it took me three weeks of late nights walking through knee-deep mud and water to capture most of the rest. My story is nothing compared to the tragedies suffered in the area just north of me in Nebraska, along the Platte and Missouri rivers, after the "Bomb Cyclone" event in winter 2019.

Dust to Mud, Drought to Flood

The new normal seems to be dust to mud, drought to flood. Maybe it has always been that way, and maybe it hasn't.

A friend shared a story from his local paper celebrating the 150th anniversary of the river-monitoring station in his hometown. According to the article, for the first 30 or so years of the station, built right after the Civil War, there was not a single flood recorded on the upstream portion of the Kansas River.

After the Homestead Act and the plowing of all the native grasslands in the area, there has been at least one flood event every single year since 1900.

What we do on the land may not control the rainfall (or *can* it? Keep reading!). The negative effects of too little or too much rainfall could certainly be mitigated, however, if our soils absorbed and held all the rainfall it received instead of letting it run off to the nearest stream, unimpeded. If rainfall could soak into the soil where it fell, maybe flooding wouldn't be such a risk. If that water were still held in the soil months later, instead of residing in the Gulf of Mexico, then perhaps the lack of rainfall would not be such a big issue either.

Fossil Fuel Addiction

The machinery we use to plant and harvest these vast acreages of food crops, along with the various machines that apply

fertilizers and pesticides, prepare the land for planting, and transport and process the food once it leaves the field, all use a tremendous amount of fossil fuel. Michael Pollan (author of the book *The Omnivore's Dilemma*) states that for every unit of energy we produce in food, we expend as much as 10 units in fossil fuel to produce, process, package, and transport that food. What happens when we run out of fossil fuels?

While all the oil discovered in the Bakken Shale may have postponed the day when we run out of fossil fuels, it is inevitable that it will eventually happen. If our entire food system requires fossil fuel to function, what happens when we have no more fuel? One can store only so much canned food in the underground bunker. At some point, we will have to uncouple our food production from fossil fuel dependence.

Fertilizer from Finite Resources

Our synthetic (non-carbon-based) fertilizers are all produced from materials that are finite in nature. Nitrogen fertilizer is produced from natural gas, while all other mineral fertilizers are produced from mined rocks. Phosphorus is of particular concern. It is used in large quantities and is found in only a few locations around the world in mineable deposits. There are some estimates that predict that, barring new discoveries, we will run out of minable phosphate reserves in 50 years at the current rate of use. (See Figure 1.4.)

Overall, our current agriculture system uses large quantities of mined fertilizers, and most of the crops containing the nutrients from these fertilizers end up in food

shipped to large cities. From there, the nutrients in food waste get flushed out into streams and eventually end up in the oceans, where they are difficult to retrieve to cycle back to the land and where they can cause additional problems.

Nutrient Enrichment of Water

All those fertilizer nutrients that end up in water—whether that is from leaching through the soil profile into groundwater, or from being washed off cropland into streams, or from being flushed into rivers from water-based sewage systems—can cause some major issues.

Nitrate in groundwater used for drinking can be converted within the intestines to nitrite, which when absorbed into the bloodstream can render the red blood cells incapable of carrying oxygen. This is of particular concern with infants, who have not yet developed enough to metabolize nitrite in the body as well as adults. This can lead to a condition known as "blue baby syndrome," so named because the inability of the red blood cells to carry oxygen causes a blue-skinned appearance in the afflicted.

The best part about adopting the principles in this book, and restoring all of the soil organic matter lost over the last 7,000 years, is that doing so will not require a sacrifice in our lifestyles or economic hardship for the world's poor.

ALGAE GROWTH

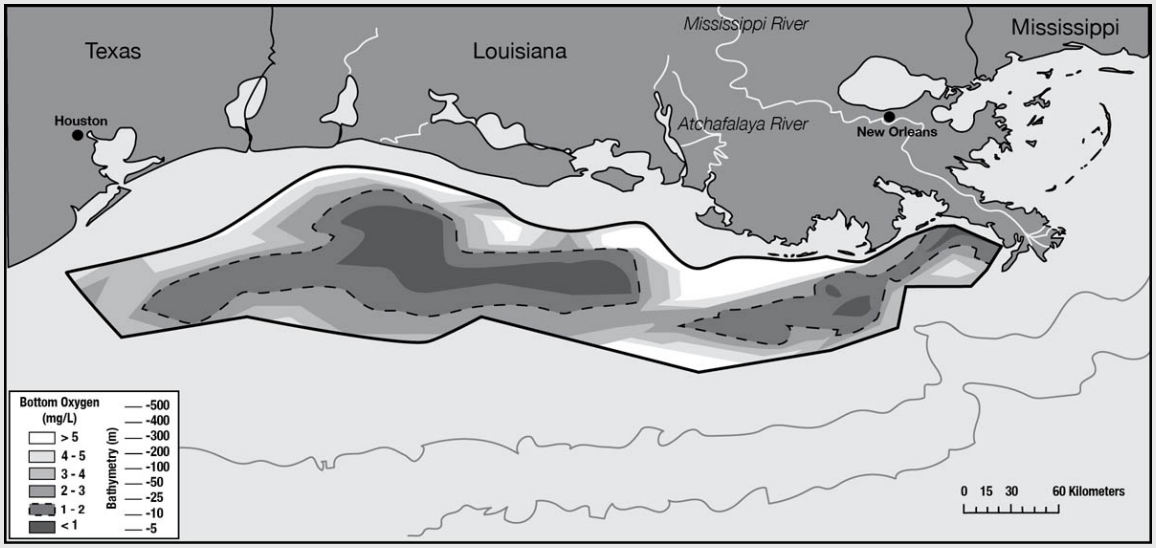
Nutrients that accumulate in unnaturally high levels in bodies of surface water can also have significant negative consequences. One of the foremost is an extreme growth of algae, called eutrophication.

Algae in moderate amounts is good. Algae produce oxygen in the water while alive, and they are the basis for all aquatic food chains. But all things that live must eventually die, and when an unnaturally large population of algae dies the bacteria involved in the decay uses up all the oxygen in the water and creates a life-threatening condition for all aquatic life that depends on oxygen in the water.

This is the cause of the hypoxic zones found at the mouth of many rivers. The hypoxic zone is particularly bad where the Mississippi River empties into the Gulf of Mexico and has throttled a once thriving shellfish industry.

Dead Zones in the Gulf of Mexico

The Gulf of Mexico has hypoxic zones around the Mississippi Delta, where an overabundance of nutrients has depleted most of the oxygen.



Source: Distribution of bottom-water dissolved oxygen, July 22–July 31, 2019. Data source: N.N. Rabalais, Louisiana State University & Louisiana Universities Marine Consortium; R.E. Turner, Louisiana State University. Funding source: NOAA

UNSAFE DRINKING WATER

Nutrient enrichment of water can also result in a proliferation of cyanobacteria (also called blue-green algae), which can form

toxins, making the water unsafe for drinking or even swimming or bathing. In my home state of Kansas, every summer there are lakes closed to recreational use because of blue-green algae.

Fertilizer runoff from farm fields is responsible for a significant amount of nutrient enrichment. We must not ignore, however, the contribution of all the city sewage and the fertilizer runoff from suburban lawns and golf courses.

I saw the results of water-testing stations along the Kansas River in 1990. The river's drainage area begins in eastern Colorado and goes all the way to Kansas City, where it empties into the Missouri River. The testing station on the downstream side of Topeka had almost double the levels of nitrogen, phosphorus, and pesticide levels as the station immediately upstream of the city. That means the city of Topeka contributed as much "agricultural" pollution as the Kansas River, which stretches 500 miles west of Topeka and drains an area of 60,000 square miles, an area bigger than the state of Iowa.

It isn't just farmers causing this problem. We all share blame.

Monocultures

In order to ease management and mechanized harvest of our crops, we grow them in monocultures. Nowhere in nature are monocultures the norm; instead, polycultures are common, with both leaf canopies and roots existing in layers that fully exploit both sunlight and soil.

Monocultures are very inefficient at using both sunlight and soil resources, because all the leaves are in one uniform layer at the same time, and all the roots are of the same type and at the same depth. The plants are predisposed to attack by insects and diseases: A pest can easily spread from plant to plant because they are touching one another. (See Figures 1.1 and 1.2.)

In nature, most ecosystems are composed of a diversity of species. That means that no one insect or disease poses much of a risk, and the distance between plants of the same species is usually far enough that pests have a hard time traveling from plant to plant.

In agriculture, we manage this problem mostly with synthetic pesticides. Monocultures dominate the landscape because they are easier to manage with pesticides, herbicides, and mechanical planting and harvesting equipment.

The World Depends on Just Five Plant Species

Worldwide, about 80 percent of all calories consumed by humans comes from just five species of plants: corn, rice, wheat, potatoes, and soybeans. What would happen if a disease or insect pest developed and decimated any one of these crops?

It isn't hard to imagine. We would witness massive starvation and, most likely, worldwide violence as the hungry try to take food from those who have it. Our dependence on so few plants for our very existence is a precarious situation for the human race.

Our Crops Are Almost All Annuals

Every plant on that list of five is an annual plant that requires harvest of seed and replanting every single year. And every single year, these plants begin anew from tiny seedlings, a stage in which the plants capture very little of the sunlight falling on the land and a period in which competing weeds must be controlled for the seedling to survive. This annual planting and weed control are responsible for much of the energy consumption in agriculture today.

Go through a grocery store aisle and look at all the plants in the produce section and the canned food section, and you can probably count on one hand the products from perennial plants. Go through the processed food sections and you will most likely find even fewer such products.

Poor Nutritional Value of Our Diets

Adding to the injury our past system of agriculture has wreaked on our environment, it has had similar effects on our diet. The ease by which grain crops and sugar crops can be mechanized, transported, and stored has resulted in these crops becoming the least expensive foods on the planet. As a result they have become a predominant part of our diet. Compared to other classes of foods, these crops are empty calories, providing little protein, vitamins, minerals, or essential fatty acids.

Reality Check in the Corner Store

Convenience stores are where many Americans obtain their first meal of the day. Recently I walked into one and, looking at the different aisles, had a bit of an awakening.

There was the sugar aisle, the starch aisle, the trans-fat aisle, the alcoholic beverage cooler, the caffeinated and sugary cold beverage cooler, and the caffeinated hot beverage brewer. Behind the counter was a nicotine shelf and a means of gambling that allows the government to collect money from poor people who are really bad at math. Oh, and out front is a fossil fuel dispenser.

Does this not explain why our country is in such poor health, despite spending the most per capita of any country in the world on health care costs? Perhaps it is because we also spend the most per capita in convenience stores and fast food restaurants.

How Did We Get Here?

Several thousand years ago, in multiple places around the world, early farmers discovered a little trick that vastly increased crop yields. They found that when they stirred the soil in some way, prior to planting, their crops grew much

better. Over time, they developed tools to stir the soil more efficiently, and then they trained livestock to pull these ever-larger implements through the field. The practice of tillage was born.

Tillage Made Civilization Possible

It was almost magical how stirring the soil caused annual plants to yield more abundantly, and it changed everything. The sudden increase in food allowed for population growth, and since it now took fewer people to feed that population, many people were freed from farming to do other tasks. A stable food supply in one location made it possible for people to build permanent houses and band together for protection and civil services.

DARK SIDES

There were, however, some dark sides to tillage. Once cultivation loosened the soil, and small-rooted annual plants replaced the massive-rooted perennials, nothing held back erosion. The precious topsoil on which most life on Earth depends began to simply wash away.

Additionally, tillage creates the conditions in which microbes can rapidly break down the organic matter in the soil. This releases all the mineral nutrients, such as nitrogen, phosphorus, and sulfur, that were stored in that organic matter. It is the release of these nutrients that causes the seemingly miraculous increase in crop growth associated with tillage.

Farmers then, and now, assume that tillage increases crop yields because soil loosening makes better conditions for root growth. In fact, it is because tillage converts stored fertility into available fertility. As noted earlier, however, it does not actually create fertility any more than a bank withdrawal creates wealth. Once the organic matter is destroyed, the soil begins to lose structure and becomes increasingly less productive.

Breaking Prairie Sod

In the early part of the European settlement of the prairie and plains regions of the American continent, the settlers faced a tough sod that was very difficult to break open with the tillage implements of the time. Consequently they saw the prairies and plains as uninhabitable, simply an obstacle on the way to Oregon or California. Then in 1837 John Deere invented the self-scouring steel plow capable of breaking prairie sod. Not long after (at least in the big scope of things) the internal combustion engine was invented, providing practically unlimited power for plowing large acreages in very little time.

From Drought to Dust

When World War I arrived and created a worldwide shortage of wheat, the high wheat prices essentially doomed the plains. Once the protective covering of sod was gone, all it took was a few years of drought and the plains turned into dust and went airborne.

If you did not have a grandparent who lived through the Dust Bowl and the incredible opportunity to hear their stories, the best substitute is to watch the Ken Burns documentary *The Dust Bowl*. It should be required viewing in every school in the nation. Even my cynical teenagers, whose school was wise enough to show it in junior high history, were impacted by this film.

Soil Conservation

The Dust Bowl did have a positive effect, though. The massive dust clouds reached Washington, D.C., just as soil scientist Hugh Bennett addressed Congress to urge the formation of the Soil Conservation Service. The story goes that Bennett knew the dust cloud was approaching and placed aides along the route of the storm. He delayed his speech until he received a call informing him the cloud had arrived, then he threw the curtains open and showed Congress, and proclaimed, "There, Gentlemen, is Oklahoma." Or something to that effect; there is no such mention in the Congressional record, just the stories told by those in attendance. P. T. Barnum had nothing on Hugh Bennett when it came to showmanship.

One of Bennett's first tasks as chief of the SCS was to send W. C. Lowdermilk on a world tour to determine how agriculture systems around the world had either succeeded or failed throughout history. The report he brought back was quite sobering (see Soil Erosion: Further Reading). Almost without exception, agriculture around the world has led to massive soil destruction.

Reversing a 7,000-Year Trend

While the issue of climate change is one of debate, there is no doubt that all life on Earth would benefit if we had more carbon in our soils, and to get it into our soils it will have to come from our atmosphere. On that we can all agree. The issue is how we can reverse a 7,000-year trend of reducing the carbon in our soil and start putting all that atmospheric carbon back into our soils, and to do it in a manner that allows us to actually make a profit.

While it sounds greedy and self-centered to mention profit when the issue is the survival of all life on Earth, the reality is that if soil restoration is not profitable, no one is going to do it, particularly in the underdeveloped areas where it is most important. Even in wealthy countries such as the US, doing the right thing is a lot more appealing if you can provide a better life for your family in the process.

Facing the Four Horsemen

War. Famine. Pestilence. Death. These are the Four Horsemen of the Apocalypse from the book of Revelations in the Bible, but also the woes of the human race since the beginning of time. All of these can be traced directly or indirectly to the abuse of soil.

Yes, you read that correctly. War, famine, pestilence, and death all arise from soil misuse. More important, the

restoration of our planet's soils can help eliminate war, famine, pestilence, and death. Let me explain.

Famine

Starvation is an inevitable consequence of soil degradation. Once a soil is eroded, it becomes increasingly difficult to raise food on it.

Pestilence

One little-known consequence of degraded soil is the declining nutrient value of the food it produces. Some nutritionists believe that much human disease is caused by an inadequate diet, and that a well-nourished person will have a healthy immune system that quickly fights off infectious diseases and such metabolic disorders as diabetes and obesity-related issues.

The first step in restoring health to our foods is to restore health to our soils. It has been found that plants grown in a healthy soil (one that is rich in beneficial microbial life) are not only richer in vitamins and minerals but also produce far more of those little-understood compounds that fight both infectious disease and cancer.

War

How does soil depletion cause war? Wars are fought over limited resources. (No one to my knowledge has ever fought a war over oxygen, despite its being vital to life. It is free and abundant.) Wars have historically been fought because someone has something a neighbor doesn't. Of course, religion and political ideology can also cause war, but hunger is a deep motivation for taking food (and the ability to produce food) from your neighbor.

Every great civilization in history has followed an almost identical path, somewhat along these stages:

1. The inhabitants discover tillage and its ability to convert stored soil wealth into immediate food. Subsequently, there is a large amount of food in one small area.
2. Blessed with this abundance of food, they settle in this one area and build permanent houses, and the availability of food frees a percentage of people to perform work other than finding food.
3. The population steadily increases.
4. Eventually, soil depletion occurs, and new land must be tilled in order to maintain the food supply. At some point, this new land extends farther and farther out until it hits a geographical boundary or extends into territory claimed by neighbors.
5. When all the soil of a village (or nation) becomes depleted, the lack of food becomes a strong motivating factor to seize land from neighbors. There is a saying that

a man without food for a day will beg, a man without food for two days will steal, a man without food for three days will fight, and a man without food for four days will kill. Neighbors naturally tend to object to this behavior, and violence ensues.

6. Violence tends to provoke revenge (violence begets violence). As Gandhi said: Eventually, an eye for an eye leaves all of us blind. Unfortunately, when we love our neighbors' land more than we love our neighbors we are predisposed to war, and the loss of loved ones due to warfare creates a hatred for our neighbors that leads to more inevitable warfare.

This pattern has occurred all throughout history: in Abu Hureyra (where archaeologists believe agriculture began in the Middle East and where some believe the Garden of Eden was located), in Babylon, in Greece, in Rome, in Jordan, in North Africa, along the Indus Valley in India, along the Yellow River in China, and in the Pueblo cultures of the American Southwest and across the United States, where the Indigenous people were forcibly removed from their land to make room for the plows of the European immigrants.

Nutrition and Soil

A good diet and lifestyle can certainly promote good health and longevity but, alarmingly, the food we eat seems to be

increasingly less nutritious. A study by Donald R. Davis of the University of Texas (*Journal of American College of Nutrition*, December 2004) compared recent nutritional analyses of supermarket produce to analyses of produce from several decades ago and found a marked decline in the vitamin and mineral content of our food in that time. Other studies have found similar results.

In addition, our diet has shifted from its prehistoric origins of fruits, nuts, leafy greens and meat (a diet low in carbohydrates, but rich in vitamins, minerals, protein, fiber, and antioxidants) to one high in sugars and processed grains (very high in calories but low in all other nutrients).

It is increasingly suspected that cancer is a condition to which we are vulnerable due to a lack of cancer-fighting agents in our food. These compounds include lycopene, lignan, soluble fiber, carotene, chlorophyll, anthocyanins, tannin, and some yet to be discovered. Many of these compounds reside in the parts of food we remove in food processing (the peel of the apple, the pulp of the orange, etc.) and are often lacking altogether in our diets, which are based largely on processed grains and refined sugars. There is increasing evidence that sugar enables cancer cells to grow.

Finally, Death

Obviously, death is a result of war, of famine, and of pestilence, but ultimately more important is the potential death of our planet. There are millions of life-forms other than humans that depend on soil for survival. Not only does depleted soil reduce productivity of food and shelter for all life-forms, but the process of soil degradation results in breakdown of soil organic matter into carbon dioxide, the primary greenhouse gas.

While fossil fuel use gains the media attention, the conversion of soil carbon into atmospheric carbon by tillage of soil is responsible for more of the CO_2 in the air than all the burning of fossil fuels in history.

“Don’t Cuss Farmers with Your Mouth Full”

When I was a kid there was a bumper sticker, commonly found on the vehicles of many farmers in my hometown, that said, “Don’t cuss farmers with your mouth full.”

We didn’t take criticism well. Most people don’t. We were quite proud of how well we farmed and believed it was simply not possible to do it any better. Any suggestion that there was a better way caused us to bristle up, and anyone who dared question us was probably just an ignorant city slicker who didn’t understand the realities of farming.

Unfortunately, that foolish pride probably set us back decades. We resisted adopting clearly better methods for far too long, because first we’d have to admit that we were not doing things in the best way already.

In hindsight, we weren’t even close. The way we were farming was in fact quite destructive to soil and would eventually lead us to ruin. We didn’t realize this, though, because over time our yields kept going up. As it turned out, this was due to better hybrids and varieties, more fertilization, higher plant populations, better equipment, and better chemicals; in other words, it was happening even though our soil was getting worse, not better.

Although we could see the gullies in our fields after a rain, we could easily erase them with tillage or a quick

pass with a dozer—it was just a part of farming, no big deal. But when this recurs every year, it is a big deal. And what happens when it happens every year for centuries?

In our defense, we didn't realize there was any other way to farm. When presented with better methods, though, we resisted. If you are a farmer reading this, many of the ideas I'll share might contradict one or many of your existing beliefs. Some might seem quite radical.

Many certainly seemed that way to me at first as well. As I examined each new idea, however, and found many of them superior to the current method, the mental barriers I had put up against new ideas became easier and easier to penetrate. I soon learned to evaluate ideas on their merits, not on my preexisting prejudices or fear of what my neighbors would think. I was often asked, "Why can't you just farm 'normal' like everyone else?" I would reply, "Because 'normal' is a synonym for 'mediocre,' and I have no desire to be mediocre."

As you read this, I urge you to stay open and evaluate these ideas objectively, on their merits, not on the fact that "no one does that around here." First try some things on a small scale. If it fails initially, try to understand why it failed, rather than dismissing it by saying, "That just doesn't work around here."

Test, evaluate, modify, and test again. Step outside your comfort zone and try something radical. You just might find that you actually prefer to "drink upstream from the herd" for a change.

Why *Do* We Still Till?

An aspect of human nature that baffles and frustrates me is that we cling to old methods of doing things, even when the evidence is overwhelming that those methods are not only ineffective but also counterproductive. Psychologists have a term for the refusal to believe evidence that contradicts a preexisting belief: cognitive dissonance. It is sustained by another activity called confirmation bias, in which a person overlooks all evidence that rejects his or her belief system and grasps the isolated bits of information that confirm it.

Plowing with Blinders On

One particular example of this behavior is the persistence of tillage as an agricultural practice. As I write this, a farmer I know is pulling a subsoiler through his fields, and his son is following him with a disk harrow to smooth out the ruts left by the subsoiler. In the spring he will disk again and follow up with another tillage pass to level the field. Then he will drive a heavy tractor and planter over it, and harvest will follow later with a 70,000-pound grain combine and 50,000-pound grain cart. He says he does this in order to loosen the soil so the roots can grow easier.

Two miles from this field, just a few years earlier, they widened the highway. To convert the loose soil in the road ditch into a compacted bed suitable for highway traffic, they first ran a subsoiler over it, then disked multiple times, and followed with a sheepsfoot packer in order to firm the soil; this

was repeated several times. In just a few days of this treatment, they had a thoroughly compacted soil on which they laid gravel and asphalt. The sequence was pretty much the same in both situations: subsoil, disk, and then multiple passes with heavy equipment.

The farmer says that he performs those operations in order to loosen soil; the engineer says he does so in order to compact it. Who is right? If you have driven down a highway and NOT sunk into the soil, I think you know the answer already. I point this out to the farmer every year, and yet every year he spends thousands of dollars in fuel and machinery repairs and depreciation in order to achieve the complete opposite of his intended effect.

How People Explain Their Fondness of Tillage

There are many reasons given for tillage by its proponents:

"It creates a better seedbed."

"It reduces crop disease and insects."

"It loosens the soil so water runs in better."

"Tillage increases yield."

Yet both practical experience and research refute these claims, as we will discuss below. There are farmers who continue to tell me tillage allows rainwater to soak in. Yet after each rain,

water is standing in the tilled fields, while there is none in the no-till field across the fence.

It must have rained more on the no-till field. It always does. The lucky guy over there with the no-till field just gets more rain. That is why his crops always yield better. He sure is lucky.

DREAM ON

This spring has had enough rain that pretty much every single tilled field in my area is covered with rills and gullies. Yet as soon as the soil dries up for a day, those farmers are right back out there tilling.

The gully may disappear from sight when it is tilled in, but that doesn't put the lost soil back uphill. How can anyone see this tragic loss of irreplaceable-in-our-lifetime soil and not feel physically ill at the sight? These same farmers will stick their hand up at a land auction and buy land for thousands of dollars an acre. They then buy equipment that costs hundreds of thousands of dollars so they can buy thousands of dollars of diesel every year for the privilege of using that equipment to slowly destroy their soil and allow it to wash away to the bottom of the reservoir downstream. In 20 years, they will pay taxes to have that reservoir dredged because it will be filled up with the soil washed from their fields.

A simple soil test can confirm that tillage causes a loss of soil organic matter over time, but people just refuse to believe it. "I have been tilling my whole life, and my soil is as good as it ever was" is a common statement. But a glance at their soil compared to the soil in adjacent pastures or grassed roadsides indicates this is absolutely not so; their soil is a lifeless, pale

brown powder, while the soil in the road ditch is rich and black and crumbly. I don't understand it.

CHANGE LOOKS HARD

I understand why tillage may be necessary in an organic farming system, due to a lack of alternatives, but in a situation where synthetic inputs are used anyway, why on earth anyone still uses tillage just mystifies me. Numerous times I have spoken at a new location and farmers have told me that "no-till just doesn't work around here."

And then I found out they have a neighbor who is successfully no-tilling across the road from them and producing significantly better yields. I know farmers who have tried no-till once, and raised their best crop ever, only to go right back to tillage the very next year.

I have two friends who farm side by side—one with no-till and cover cropping, the other with conventional tillage. In the drought of 2012, they planted the exact same soybean variety across the fence line from each other on the same day. Come harvest time, the beans planted without tillage into "that mess" of a killed cover crop made 52 bushel an acre (I repeat: this in the drought year of 2012), while the beans in bare soil made 25. This pattern repeats itself annually, but still the conventional tillage guy still believes "you just can't raise a good crop without tillage."

GOT TO DRIVE THAT TRACTOR

The best explanation is that some farmers just like to till. They spend borrowed money to buy a $250,000 tractor to pull a

$100,000 tillage implement so they can destroy their $6,000-an-acre land because they just like to sit in that air-conditioned cab and feel the power of that diesel engine underneath them and stir that dirt up and feel like they are accomplishing something. It makes them happy. And any evidence that points out the devastation caused by tillage interferes with this happiness, so it is ignored.

Our Father, the No-Till Convert

At one time my father would bristle up and his face would turn red at the mere mention of no-till. Then my brother took a job as an agronomist in an area with several successful no-till farmers. I had also taken a job as an agronomist and had 180 clients, a third of whom were no-till, and the top half of those were our very finest farmers.

We reported these successes to our father (quite gingerly at first!) and showed him some no-till fields. Intrigued, but not yet convinced, he started experimenting with it, reducing his tillage on most of his crops while still firmly believing that corn needed preplant tillage.

SEEING THE LIGHT, IN THE RAIN

One day he was doing preplant tillage prior to planting corn, and it began to rain. It was soon pelting so hard that he shut off the tractor in the middle of the field and sat there in the cab, not wanting to go out in the downpour. And he saw the rain wash away every inch of the soil he had just tilled, while the part of the field that was not worked was still intact.

That year, the difference between the two sections of the field was night and day. The part missing its topsoil resulted in complete crop failure, and the other half produced a respectable yield. It dawned on him that this single tillage trip was a lifetime mistake, and one he had made hundreds of times.

Yes, the university extension people said no-till would not work on our heavy clay with low organic matter and poor structure and drainage. What they didn't tell us was that the low organic matter and poor structure were caused by tillage in the first place. It seems that tillage didn't work very well, either.

My father resolved to make no-till work in an area where the "experts" said it wouldn't. Luckily, he and a handful of like-minded farmers in the area all leaned on one another for support, sharing successes and determining reasons for failure. Amazingly (or perhaps not!), they were successful. Yields did not plummet, and in fact they somewhat improved.

Every year I tilled, my soil got worse, and every year it took more tillage to accomplish the same result. Every year I no-till, the soil gets better.

TAKING THE LONG VIEW

My father is now one of the biggest no-till advocates in his area. He once told me something that made a huge impression: "Every year I tilled, my soil got worse, and every year it took more tillage to accomplish the same result. Every year I no-till,

the soil gets better. If I keep no-tilling long enough, my soil will get a lot better. If I had kept tilling long enough, it would have gotten a lot worse. I just thought to myself, 'What condition do I want my soil to be in when I leave this world?'"

And that is exactly the point. We MUST think in terms longer than the next harvest. While people may question whether they can raise better crops with or without tillage, there is one point for which there is no dispute: The long-term effect of continued tillage is drastically deteriorated soil. Anyone who says otherwise is simply ignoring the evidence in front of their eyes. (See Figure 9.1.)

7 HARMFUL EFFECTS OF TILLAGE: SOME EVIDENCE

Tillage destroys soil structure, reduces organic matter, reduces rooting depth, triggers soil erosion, reduces water infiltration, and is expensive as well. Throughout history, every civilization that depended on tillage-based agriculture for its food supply has eventually collapsed, with few exceptions. If the human race is to survive on this planet, we will need soil that gets better every year, not soil that gets worse. There's no question about the path we need to take. We need to eliminate tillage as an agricultural practice.

Perhaps the reason many people haven't given up tillage is that the damage is so often slow, occurring in such small increments that it is hard to see. And the typical farmer has no convenient way to compare the effects. Scientists are on the case, however: Here is research data that illustrates some of the negative effects. You can find many other books and articles that support these points. The data shown are typical examples.

1. TILLAGE INCREASES SOIL EROSION.

How Different Tillage Methods Affect Soil Erosion and Rainfall Runoff

	MOLDBOARD PLOW	MULCH TILL	NO-TILL
Avg soil loss, kg/ha	178.3 +/- 11.68	131.2 +/- 3.91	113.2 +/- 3.62
Avg runoff, cubic meters/ha	7.30 +/- .34	6.25 +/- .34	5.94 +/- .37

Source: M. Vach, L. Hlisnikovsky, and M. Javurek, "Effects of different tillage methods on erosion," *Agriculture* 64, no. 1 (2018): 28–34.

2. TILLAGE DESTROYS SOIL STRUCTURE.

How Tillage Affects Aggregate Stability

How Tillage Affects Aggregate Stability

	PLOW	REDUCED TILL	NO-TILL
% Water-Stable Aggregates	59.5	70.09	70.74

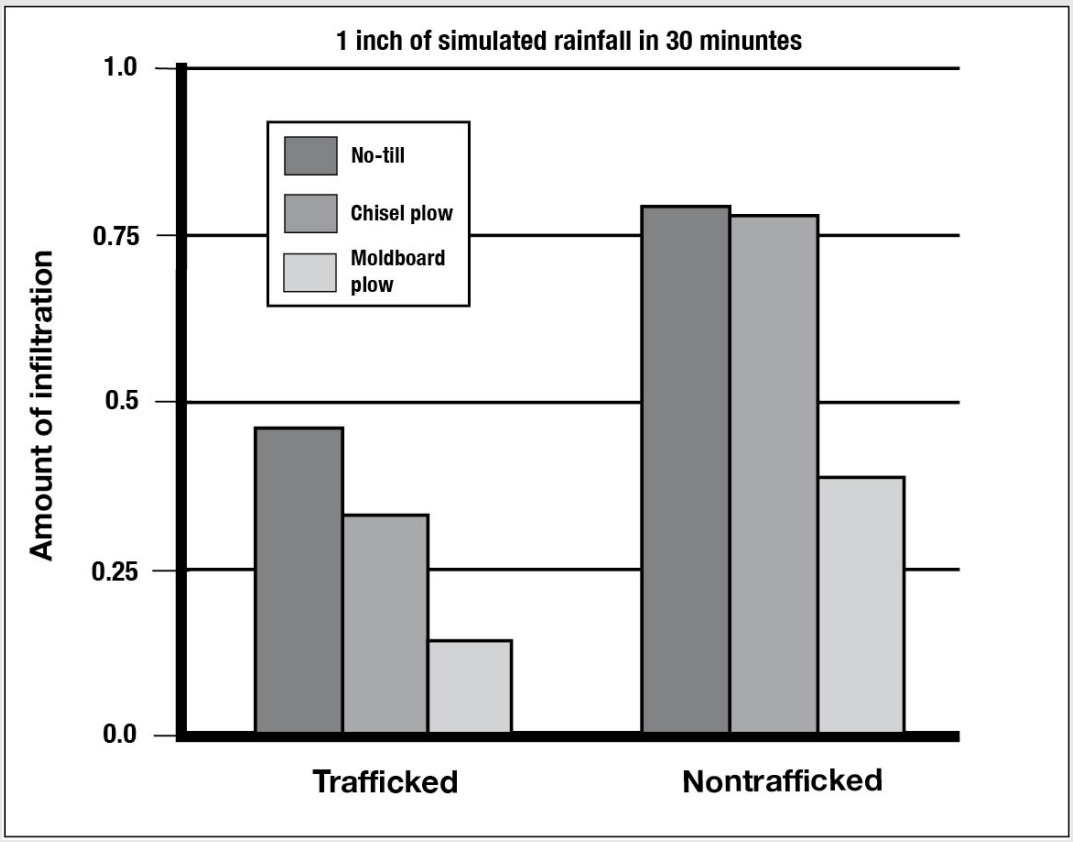
SOURCE: J. Somasundaram, A. K. Biswas, N. K. Sinha, M. Mohanty, K. M. Hati, P. Jha, M. Sankar, A. K. Patra, R. Dalal, and S. K. Chaudhari, "Effect of contrasting tillage and cropping systems on soil aggregation, carbon pools and aggregate-associated carbon in rainfed Vertisols," *Soil Science* 69, no. 5 (September 2018).

3. TILLAGE REDUCES RAINFALL INFILTRATION.

How Different Tillage Methods Affect Rainfall Infiltration

SOURCE: "Long-term tillage effects on corn and soybean yields in the Piedmont," *North Carolina Extension Publication* AG 439–80 (January 20, 2015).

How Different Tillage Methods Affect Rainfall Infiltration



SOURCE: "Long-term tillage effects on corn and soybean yields in the Piedmont," *North Carolina Extension Publication* AG 439–80 (January 20, 2015).

4. TILLAGE REDUCES ROOT MASS OF THE CROPS THAT FOLLOW.

How Tillage Affects Corn Root Weight

TILLAGE SYSTEM

How Tillage Affects Corn Root Weight

	PLOW	CHISEL	NO-TILL
SOIL DEPTH	ROOT WEIGHT (MILLIGRAM PER CUBIC CENTIMETER)		
0 to 3 inches	0.75	0.83	1.88
3 to 6 inches	0.98	0.98	0.75
6 to 9 inches	0.51	0.50	0.50
9 to 12 inches	0.23	0.22	0.23

Note that in this trial, tillage actually decreased the number of shallow roots (in other words, roots did NOT grow better in soil loosened by tillage) and tillage also did not help roots grow deeper.

SOURCE: D. B. Mengel, "Fertilizing Corn Grown Using Conservation Tillage," *Agronomy Guide AY-268*, Purdue University Cooperative Extension Service (1990).

5. TILLAGE REDUCES SOIL ORGANIC MATTER.

How Tillage Affects Soil Organic Matter

SOURCE: H. P. Denton, and D. D. Tyler, "Making No-till Conventional in Tennessee," *Proceedings of 25th Southern Conservation Tillage Conference* (2002).

How Tillage Affects Soil Organic Matter

	CARBON CONTENT, MG/HA	
SOIL DEPTH, INCHES (CM)	NO-TILL	TILLED
0–3 (0–7.5)	2.4%	1.1%
3–6	1.2%	1.3%

SOURCE: H. P. Denton, and D. D. Tyler, "Making No-till Conventional in Tennessee," *Proceedings of 25th Southern Conservation Tillage Conference* (2002).

6. TILLAGE USES A LOT OF FOSSIL FUEL AND COSTS A LOT OF MONEY.

How Costs of Different Tillage and Planting Operations Compare

OPERATION	COST, $ PER ACRE	FUEL USE, GALLONS PER ACRE
Moldboard plow	39.80	2.1
Tandem disk	12.60	0.5
V-ripper	22.50	1.5

SOURCE: D. Lattz and G. Schnitkey. "Machinery Cost Estimates for 2019." *farmdoc daily* (9):144, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, August 6, 2019.

How Costs of Different Tillage and Planting Operations Compare

Field cultivator	9.90	0.3
Vertical till	11.70	0.4
Conventional planter	14.40	0.3
No-till plant	17.20	0.5
No-till drill	25.80	0.9

SOURCE: D. Lattz and G. Schnitkey. "Machinery Cost Estimates for 2019." *farmdoc daily* (9):144, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, August 6, 2019.

7. TILLAGE SENDS A GREAT DEAL OF CO_2 EMISSIONS INTO THE ATMOSPHERE.

How Tillage Affects CO_2 Emissions from Soil into the Atmosphere

	NO-TILL	REDUCED TILL	MOLDBOARD PLOW

SOURCE: K. Kristof, T. Sima, L. Nozdrovicky, and P. Findura, "The Effect of Soil Tillage Intensity on Carbon Dioxide Emissions Released from Soil into the Atmosphere," *Agronomy Research* 12, no. 1 (2014): 115–120.

How Tillage Affects CO_2 Emissions from Soil into the Atmosphere

CO_2 released, micro mol/cubic meter/second	2.014	2.889	4.318

SOURCE: K. Kristof, T. Sima, L. Nozdrovicky, and P. Findura, "The Effect of Soil Tillage Intensity on Carbon Dioxide Emissions Released from Soil into the Atmosphere," *Agronomy Research* 12, no. 1 (2014): 115–120.

The Real Effects of Fallow

After tillage, perhaps the next most destructive practice in agriculture is that of fallow. Fallow has been practiced to some extent all over the world but is used most extensively in the drier areas.

The idea seemed sound: Let the soil accumulate moisture by not allowing any plant growth. The tillage used during the fallow period oxidized organic matter and resulted in an accumulation of available minerals, in addition to increased soil moisture. The combination of extra water and extra fertility resulted in an increase in subsequent crop yields, leading to fallow becoming a widely used practice.

But fallow had some drawbacks, both obvious and hidden:

- It required several months of sunlight—wasted sunlight—to produce this accumulation of soil fertility and moisture.
- It proved very inefficient in moisture use. According to one study by Kansas State University, a 10-month fallow period stored only 17 percent of the rainfall that occurred in a tilled soil, compared to 33 percent in a no-till trial.
- The increase in available minerals came about through a reduction of soil organic matter.
- During fallow, the efficiency of sunlight use is zero percent. None of the sunlight falling on land is captured or put to use during a fallow.
- Without plants growing for a year, there are no organic matter inputs into the soil for a year. As soil organic matter decreases, so does the ability of soil to take in and store rainwater.

Loss of Soil Microbes

The most insidious shortcoming of fallow is the elimination of the soil organisms that depend on live roots for their survival. Microbes have relatively short life spans and need to be fed constantly. When the soil has no live roots for 9 to 18 months, these organisms simply starve. Some of these organisms are the very same organisms that would increase drought tolerance (you'll learn more about soil biology in Chapter 5).

The benefits of fallow are short-lived, but the drawbacks are very long-lasting. Fallow does not "rest" soil; it starves it!

“But I Get Better Yields When I Till!”

I often hear this statement from farmers defending tillage, and they are not incorrect. Tillage can increase yields by creating pore spaces, allowing more oxygen into the soil for more root growth—but this is a temporary effect. Tillage also reduces soil oxygenation over the long term by destroying soil aggregates (see here), creating the need for more tillage over time to get the same effect.

Tillage increases crop yields the same way a shot of whiskey “cures” alcoholism. It doesn’t increase productivity; it just temporarily alleviates the symptoms caused by tillage in the first place.

Another seeming “benefit” of tillage is that as the soil organic matter gets oxidized it releases plant nutrients, particularly nitrogen. If this seems like fertilizer for free, it is not; it is fertility taken out of savings to be used today, at the expense of soil structure and water-holding capacity. It creates fertilizer no more successfully than a debit card creates money.

Tillage is a road to eventual ruin, whether it occurs in our lifetime or our grandchildren’s or their grandchildren’s. This book focuses instead on the soil characteristics that increase productivity, and the practices that can support and improve those characteristics.

CHAPTER 2 SUMMARY

- Agriculture has increased greatly in productivity over the years, but it has come at a price.
- Problems that have occurred due to agriculture include:
  - soil erosion
  - loss of soil carbon and increased atmospheric carbon dioxide
  - increases in flooding and a reduction in water use efficiency
  - an increased dependency on fossil fuel
  - an increased scarcity of fertilizer materials
  - pollution of water and soil
  - declining health of our environment and in the nutritional value of the food we produce.
- Much of this degradation comes from two very common agricultural practices: tillage and fallow. Improving the environmental impact and profitability of our world's food production depends largely on eliminating these two practices.
- Tillage can temporarily increase crop yields, but this comes at the expense of long-term productivity. Tillage has the

following negative effects:

- increased soil erosion
- degradation of soil structure
- reduced infiltration of rainfall
- decreased root mass of plants over time
- decreased soil organic matter
- increased fossil fuel use and expense
- increased atmospheric CO_2 emissions

- Fallow, another common practice, is a period when all plant growth is prevented in order to store soil moisture for use by the next crop. This can increase the yield of the next crop in rotation, but again it comes at a price. Plant growth is necessary for these reasons:
  - It feeds soil microbes that are essential to help plants extract water from the soil.
  - It builds soil organic matter, which aids water-holding capacity.
  - In short, fallow starves soil microbes and reduces the long-term drought tolerance of soil.

PART II

What Is the Ideal Soil?

The role of soil is to provide physical support for the plant, offer water, allow enough oxygen to the roots, and furnish mineral nutrients. It all seems very straightforward. With unlimited free access to irrigation water, a very well-drained porous soil (such as sand), and abundant cheap fertilizer, this can all be accomplished rather easily.

In most soils, however, it is not this simple.

03

Soil Oxygen

When we think of limiting factors in the soil for plant growth, our mind usually focuses on water and mineral nutrients. Seldom do we think of oxygen as a limiting factor, but oxygen is absolutely vital not only to plant roots but also to most soil organisms. Without sufficient oxygen, roots cannot penetrate very far into the soil and thus cannot access much of the water or minerals found in the soil.

Lack of soil oxygenation probably is far more limiting to plant growth and soil biology than any of us suspect; if that is indeed the case, overcoming the lack of soil oxygenation may be a key to vastly improving crop yields.

The Elements of Soil Productivity

Under a microscope, sandy soil resembles a pile of little balls, and water and air can move readily through the gaps. (See Figure 2.3.) The sandy soils that tend to be well oxygenated lack the ability to hold much fertility, however, because there is very little relative surface area to hold it. The ability to hold mineral nutrients is often measured in terms of **cation exchange**. Cations are ions with a positive charge, and surfaces of soil particles are typically negatively charged, so cations adhere to them by magnetic attraction. Most of the nutrients required by plants are taken up as cations. Sandy soil is low in cation exchange.

Clay soils are very high in cation exchange but are usually poorly aerated and therefore lack the oxygen needed for active transport. Under a microscope, clay looks like stacks of paper. It is composed of many flat sheets. The spaces in between these sheets can hold a tremendous amount of water and nutrients, just like a sheet of paper can hold a lot of writing on it. (See

Figure 2.2.)But these stacks of sheets are not conducive to allowing oxygen into the soil. Also, water moves quite slowly through clay because, in order for water to enter, air must have an escape route. Clay soils also tend to "fix" many nutrients into unavailable forms, while sandy soils lack the ability to hold nutrients in the root zone and allow them to leach below the roots.

Ideally, for optimal plant growth, water, mineral nutrients, and oxygen must be provided to the same root at the same time. At first glance, this seems impossible and, in the current state of many agricultural soils, it is. Most agricultural soils oscillate between too little water and too little oxygen, with good nutrient uptake taking place only in the brief transition periods between. The question then arises: How can you accomplish the seemingly impossible task of providing water, oxygen, and minerals to the same root at the same time?

For most of the past 7,000 years we have tried to make soils more productive through physical means, primarily through tillage, which by now you should realize was a misguided path. For the past 150 years, however, we have largely attempted to make soils more productive through chemical means: by adding fertilizers and by controlling insects, weeds, and diseases through chemical compounds that often end in the suffix "-cide."

Biology Leads the Way

Now we are on the cusp of a new revolution in agriculture, one that is based on the realization that almost all problems of soil

productivity can be addressed through biological means, primarily through microbes. It is not that soil chemical and physical conditions are not important, because they are, but we now realize the incredible power that microbes have to create optimal conditions for plant growth in almost any soil.

FIVE STEPS TO PRODUCTIVITY

Crucial to this thought process is the understanding that this increase in productivity is not achieved by pouring something out of a jug, even if the contents of that jug are microbes ("bugs in a jug"). Rather, it is achieved by:

1. Capturing and directing energy to soil microbes. This energy is derived from . . .
2. Photosynthesis, which is carried into the soil in the form of carbon compounds. This requires . . .
3. Plant growth, which we nurture by . . .
4. Creating optimal conditions for plant growth (namely sunlight, soil minerals, water, carbon dioxide, and soil oxygen); and by . . .
5. Creating optimal conditions (temperature, moisture, etc.) for the soil organisms that are the real producers of healthy, productive soil.

Tilling with Dynamite

FROM THE COLONY (KANSAS) *FREE PRESS* IN 1909

Nov. 5, 1909. As per arrangements, the DuPont people were on hand Wednesday to dynamite the acre of land that had been prepared for them on the C.H. Clark farm. About 150 people witnessed with interest. The object was to loosen up the subsoil allowing the air to more freely penetrate, thus starting a process of pulverizing the soil to a great depth, bringing the potash and nitrogen into action to assist in growing of crops. It is thought by Ex-Gov. S. J. Crawford and A. J. Georgia of Pittsburg, KS, that the experiment is a profitable one. J. W. Williams of Central Kansas, an extensive alfalfa grower, said he took an acre of gumbo soil that was worthless for crop, but after dynamiting the ground and sowing it to alfalfa he was able to cut three crops of alfalfa from the land in one year.

Howard Hester has one of the best orchards in this section and states that his orchard ground was first dynamited before the setting of trees some twenty years ago. It is claimed by Crawford and

others that there is more potash and nitrogen in the heavy gumbo and hard pan soil than any other soil, and loosening it up and allowing the hard soil to become pulverized provides access to growing crops.

Author's note: Howard Hester was my great-great-grandfather. As I have mentioned, the soil where I grew up was extremely heavy clay underlain with limestone bedrock at a shallow depth. When my great-grandfather (Howard's eventual son-in-law, Claude Strickler) hired a man to first plow the native grass sod south of his house on this same farm, the plow man completed the job and said, "Claude, if I had this farm and a house in hell, I think I would sell this farm and go home."

Sometimes extreme measures were taken to loosen this soil and introduce oxygen. Now, over a hundred years later, we know that the secret to loosening clay soil and aerating it is not explosives, nor a plow; it is soil microbes. (Though I can tell you that dynamite was certainly a fun method to try! It doesn't really loosen clay soil much, long term, but it sure busts up limestone bedrock.)

Today, by following many of the ideas in this book, my brother is now consistently raising 150 bushel-per-acre corn on the land that, Claude Strickler was told 100 years ago, was less preferable than a house in hell.

Getting Oxygen into Soil

Lack of root depth creates a situation in which plants often have an insufficient supply of either moisture or mineral nutrients, neither of which is conducive to plant growth or soil improvement. It is often assumed that mechanical barriers (hardpans) are the reason that roots fail to penetrate, but an observation of how tree roots frequently break concrete sidewalks along city streets illustrates that a simple hard soil is seldom a real barrier to root growth.

In reality, what is most often limiting to root depth is a lack of oxygen. Aboveground, oxygen is seldom a limiting factor for growth, since the atmosphere contains 21 percent oxygen. Below the soil surface, however, oxygen is quite often the most limiting factor for growth of both roots and microbes, as respiration by both can use up much of the supply faster than it can move into the soil. Although some microbes can function in anaerobic conditions, the majority of microbes, and nearly all beneficial ones, require a minimum amount of oxygen. Plant roots need at least 10 percent oxygen to thrive.

What Keeps Oxygen Out of Soil?

Factors that prevent movement of oxygen into the soil include saturated conditions, poor drainage, compaction, excess sodium, lack of organic matter, and poor structure caused by tillage. Tillage, particularly subsoiling, can introduce a large amount of oxygen into the soil, although this also results in the oxidation of organic matter and eventually results in further

degradation of soil structure and, over time, even less oxygen content.

This is why it is said that soils become “addicted” to tillage. Any inversion tillage operation, such as disking or plowing, will result in a loosening of surface soil. But in order to lift the soil above the surface, the tillage implement has to push down on the soil. This results in formation of a plowpan, with a platy structure that greatly restricts the movement of oxygen into the soil. (See Figure 2.4.)

How best to remedy this is a matter of controversy. Conventional wisdom is to use a subsoiler and mechanically cut a slot through the soil. While this works temporarily, research has shown that one subsoiler trip results in a massive loss of organic matter and a destruction of soil aggregates—the opposite of what we want. Since virtually all cropped soils were moldboard plowed at one time, finding a remedy for this situation that does not involve destructive tillage is paramount.

Identifying a Lack of Oxygen

It is usually a simple matter to determine if a subsoil is lacking in oxygen in a temperate area.

ROOTS IN THE SUBSOIL

The presence or absence of roots is the first clue. Simply dig a hole and look at the soil. If roots are present, then oxygen is apparently not limited or limiting in that layer. If roots are

lacking, however, it may indicate a lack of oxygen or it could be another factor.

SUBSOIL COLOR

If the subsoil is red or reddish brown, it has enough oxygen for root growth. If it has a gray coloration, it lacks oxygen. This color shift derives from the iron compounds in the subsoil converting either to the oxidized (red) tint in the presence of oxygen or to the reduced (gray) forms in the absence of oxygen. (See Figure 2.5.) Subsoils rust just the way iron does when exposed to oxygen and moisture.

Intermittent oxidation can cause a yellow subsoil color. Incomplete oxidation will usually result in a mottled appearance of red streaks on a gray background. Often these red streaks will follow a crack, a worm burrow, or an old root channel where oxygen can penetrate a little farther. This is our clue to remedy the situation of poor oxygen penetration.

Sometimes a lack of oxygen is caused by a high subsoil water table, usually indicated by a solid gray subsoil. This can be remedied only by subsurface drainage. If the cause is the presence of compacted or platy soil layers, however, there are some other, cheaper remedies, discussed below (Preventing Soil Compaction).

Subsurface Drainage

With soils that typically have a high water table in spring, subsurface drainage can increase root depth, thereby improving drought tolerance later in the season. It is often

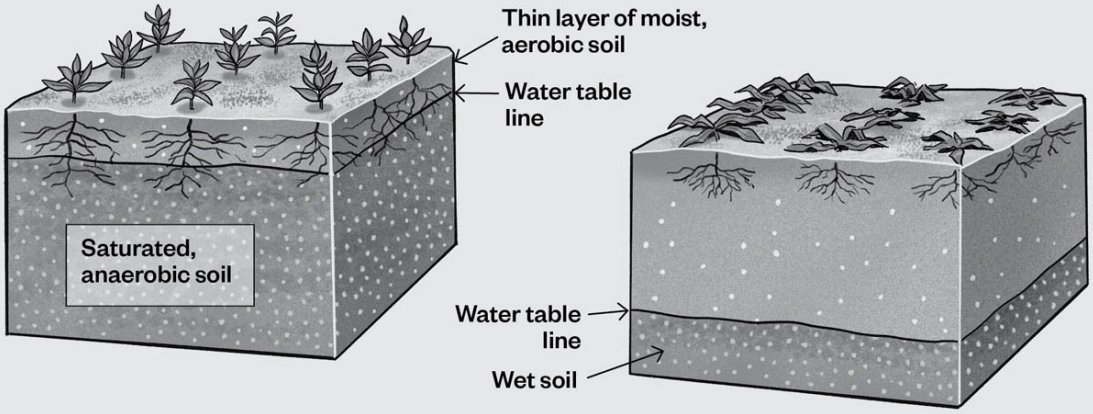
referred to as tile drainage, because it used to be constructed of clay tiles (short sections of interlocked ceramic pipes). These days, most subsurface drainage is accomplished with perforated, corrugated plastic tubing (see Subsurface Drainage).

It seems counterintuitive that removing water from the soil can improve performance of crops in a drought, but the key is not the removal of water; it is the entry of oxygen into the soil when pore spaces are drained of water. Roots need both oxygen and moisture in order to grow, and a saturated soil will not have oxygen. By draining away the excess water that usually occurs in spring in many areas, roots can grow deeper and be more able to access soil moisture when the typical late summer drought occurs. Tile drains can also remove water from ponded areas, such as the areas just uphill of terraces, to prevent crops from drowning out.

Subsurface drainage can greatly increase the productivity of cropland in wetter areas, such as the northeastern US and the eastern Corn Belt; however, it can also have negative effects on the environment. One is that tile drains can become an easy pathway for nitrates or pesticides leached out of the soil profile to enter waterways (see Chapter 6). Another is that tile drainage systems have made it feasible to convert large areas of wetlands to cropland. While this is an obvious economic boon for the landowner, it is an ecological loss, as wetlands perform many valuable functions.

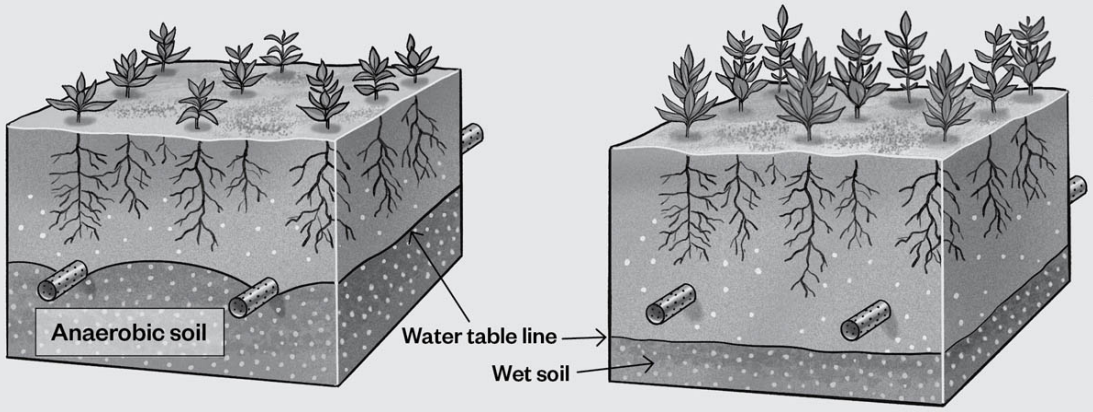
SUBSURFACE DRAINAGE

Before Drainage



ABOVE: *LEFT: During a wet spring, saturated, anaerobic soil is close to the surface, preventing full root growth.* *RIGHT: Later, in summer drought, roots are shallow and cannot reach moist soil.*

After Drainage



ABOVE: *LEFT:During a wet spring, anaerobic soil is far from the surface, allowing full root growth.* *RIGHT: Later, in summer drought, roots are deep.*

Preventing Soil Compaction

In addition to poor drainage, the other main cause of less-than-optimal soil aeration is compaction. As we will discuss later, compaction is best alleviated through biological means rather than mechanical ones. It is much easier to prevent compaction, however, than it is to correct it once it has occurred. Here are the primary strategies to prevent soil compaction:

- **Eliminate tillage**. Tillage destroys soil aggregates and makes soil more susceptible to compaction.

- **Reduce vehicle traffic on the field.** Combining operations into a single pass may help achieve this. For example, putting a sprayer onto a planter may eliminate the need for a separate trip with a sprayer.
- **Use vehicles with tracks** rather than wheels. Tracks have been found to compact soil much less than wheels.
- **Use controlled traffic patterns** to keep all vehicle tires on the same narrow paths.
- **Reduce equipment weight.** Using equipment that is not oversized helps reduce compaction and saves fuel. Farmers who convert from a tillage system to no-till typically can reduce the size of the tractor they need. But not all do so; they all too often hang onto that big old fuel guzzler "just in case" they "need" to do some tillage.
- **Stay off fields when they're wet.** Wet soils are more susceptible to compaction than dry soils.
- **Keep a residue layer on the field.** The residue acts somewhat like snowshoes to help hold up vehicles.
- **Keep live roots in the soil** to create a firm sod-like condition that resists compaction. Cover crops are excellent for accomplishing this, as is including perennial forage crops in the crop rotation.

The Soil / Oxygen Cycle

Understanding the seasonal changes in soil oxygen levels is critical to improving the soil/oxygen cycle. Old, decayed root channels can provide passages through oxygen-limiting layers,

but the challenge lies in creating those channels in the first place. Oxygen levels fluctuate throughout the year, and we can take advantage of this knowledge.

COOL-SEASON ACTIVITY

When the soil is warm, microbes consume the vast majority of oxygen as it enters the soil. When the soil temperature drops below 55°F (13°C), microbial activity ceases and the oxygen in the soil increases to annual high levels. The roots of cool-season plants can grow at soil temperatures below 55°F if the ground is not frozen. Thus, there is a window in fall and a window in spring when the soil temperature is between 32°F and 55°F (0°C and 11°C) and during which roots of some plants can penetrate soil layers that would be impenetrable in summer.

Some cool-season plants that can exploit this phenomenon include annual ryegrass, tall fescue, and most brassicas—with forage radish being the most effective. Incorporating these plants into a crop rotation or pasture system can provide the initial "pioneer" roots that make the first penetration through an oxygen-limiting layer. (See Figure 9.4.)

Fragipans are dense clay layers in the soil that are hardened by deposits of cementing agents like iron oxide, and they act as a strong barrier to root penetration. Ryegrass appears to be able to produce root exudates (sugary liquid that oozes out of roots) that chemically dissolve fragipans, as indicated by research done by L. W. Murdock at the University of Kentucky (see For Further Reference). According to Murdock's research,

each year that annual ryegrass grew on a soil, the thickness of the fragipan decreased by roughly 1 inch.

LEARNING FROM PLANTS

Another mechanism for penetrating oxygen-limiting layers is to look at plants that naturally grow in low-oxygen soils, identify ones that root deeply in those conditions, then figure out what makes them capable of doing so.

One mechanism that allows this to happen is a tissue in plant roots called **aerenchyma**. Aerenchyma tissue is found in some plant roots and stems and features hollow spaces for the passage of air down through root channels. This allows roots to penetrate soil layers that otherwise have insufficient oxygen to support root growth. Aerenchyma tissue is found in many plants that naturally populate marginal wetlands, where soil oxygen levels are typically low. Most of these wetland-type plants do not have economic value, are not useful forage plants, and do not lend themselves to soil-building efforts via ruminant animals.

Two forage plants that have prominent amounts of aerenchyma tissue are eastern gamagrass and reed canarygrass. Both of these plants are perennial forage grasses and are rather slow to establish. Using them to improve soils thus requires a commitment of several years to pasture. Eastern gamagrass stands typically increase in productivity every year until about 10 to 15 years of age, then they plateau. Anecdotal reports indicate that corn and soybean crops grown on old gamagrass fields outyield the crops on neighboring fields by roughly 10 percent.

DIGGING DEEPER

Once oxygen-limiting layers are penetrated, the soil depths can be utilized by other plants with potentially deep root systems such as alfalfa. When the effective root depth is increased, the ability of the soil to supply water and nutrients is greatly enhanced. This leads to more biomass, which leads to more organic matter, which leads to better aggregate stability, which leads to better oxygen penetration, which leads to even better root depth, and so on. Once the cycle is initiated with the right pioneer plants, it becomes self-perpetuating and ever-improving.

It is also critical to maintain live roots throughout the entire year. The best remedy for low-oxygen soil is to improve soil aggregation. Aggregation is performed by soil microbes, particularly soil fungi. These organisms are fed primarily through root exudates. Thus, maintaining a live root fed by photosynthesis for as much of the year as possible is critical to feeding soil aggregating microbes. The single best class of organisms for soil aggregation is mycorrhizal fungi (MF), through their secretion of glomalin. Mycorrhizal fungi are discussed at length in Chapter 5.

Though the cause of compaction is often a mechanical action such as tillage or traffic, and the primary negative effect is chemical in nature (a lack of oxygen to the roots), the remedy to compaction is neither mechanical nor chemical; it is to nourish soil microbes that improve aggregation.

Glues That Hold the Earth Together

The real key to creating better soil is to glue the sand, silt, and clay into little round balls called aggregates. These hold water in small internal pores yet allow the movement of air and water between. Clearly, this requires some sort of binder or glue to make this happen. But where does this glue come from?

The answer lies in soil organisms, both large and small. Plants, fungi, bacteria, and animals all secrete glue-like substances that can perform these functions. The most important of these are undoubtedly plants, not so much because they are the best at aggregating soil, but because the energy they derive from photosynthesis fuels the entire belowground ecosystem. Without plants, none of the other organisms have energy required to live.

This explains why our agriculture systems based on annual crops—which lack live root systems for much of the year—so often cause soil degradation. Therefore, Job Number One is to create live plant cover for as much of the year as possible. This will convert more solar energy into biologically available energy for aggregation processes. We will go further in depth on how to improve solar energy capture throughout the year in Chapter 7.

Besides producing food for microbes, plants also have an aggregating effect. Plant root tips secrete a lubricant to aid root expansion called **mucigel**. Mucigel is a complex polysaccharide that contains sugars, amino acids, and other

substances that tend to be highly absorptive of water, and it acts as a perfect growing medium for a number of beneficial microbes.

The plan for increasing the aggregating effect of plant roots is quite simple: grow more plant material. This can often be accomplished on cropland by adding cover crops to the rotation.

Feeding Earthworms and Other Soil Life

One of the biggest benefits of plants is that they nourish the organisms in the soil, and they do this when they're alive or dead. Dead plant material nourishes an entire spectrum of soil organisms, one of the most visible and beneficial of these being earthworms. (But a far bigger contribution of plants to soil microbes comes from the root exudates, which are discussed in detail in Chapter 5.)

Earthworms feed on dead plant material, incorporating it into a blend with soil particles as they burrow. They pass this digested blend of plant material and soil particles into an incredible growing medium called a **worm cast**. It seems like alchemy, but a chemical analysis of a worm cast shows that it contains far more available plant nutrients than the soil surrounding it. In addition, these casts demonstrate tremendous aggregate stability, being very durable and having an ideal shape and size for the perfect blend of availability of both soil water and air. (See Figure 3.2.)

But wait! There's more! As they pass through the soil, earthworms also secrete a lubricant, somewhat like the

mucigel that plant roots secrete. This lubricant, or slime, lines earthworm tunnels and holds them open. A microbial analysis of the lining of earthworm tunnels shows a far more diverse and abundant microbial population than that found in the surrounding soil. The stability and size of earthworm tunnels allows them to serve as passages for the movement of both air and water.

The movement of the earthworms themselves acts almost like a piston to push the soil air (high in CO_2 and low in O_2) out of their tunnels in the evening as they exit to feed at the surface (though not all earthworms are surface feeders). This creates a vacuum in the soil that is filled by the influx of fresh, high-oxygen air. See How to Help Earthworms Thrive for effective methods of supporting earthworm life and activity.

The Miracle of Microbial Glue

There is a way to develop the ideal soil that is half solid and half pore space, with the pore space holding a balanced amount of water and oxygenated air. A soil with very tight pore spaces, such as clay, is very good at holding water. A soil with large pore spaces and round particles, such as sand, is good at admitting oxygen.

The way to have the best of both worlds is to make little “popcorn balls” out of the soil by binding sand, silt, and clay into large, spherical **aggregates**. Water is held inside the aggregates between the spaces of the small particles, but

oxygen moves freely around the aggregates, diffusing inside them. *Voilà!* The roots have water, minerals, and oxygen in the same place at the same time.

No matter the percentage of sand, silt, and clay in the base soil, this miracle can be accomplished through the production of microbial glues that cement the soil together into aggregates. These glues can be produced by bacteria and earthworms, but the most powerful producers are a group of symbiotic fungi, called **mycorrhizal fungi**, that colonize plant roots. The glues that hold these aggregates together also have considerable cation exchange themselves, improving the ability of the soil to hold both water and mineral nutrients.

The action of these biological agents also improves nutrient availability by converting unavailable nutrients into available ones. The organic compounds that form the glues will **chelate** many nutrients, which means they will loosely sequester nutrients into a form available to plants but keep them from being converted by other soil minerals into unavailable forms.

Though the problems of virtually any soil are physical and chemical in nature, the solution to almost all those problems is biological: enhancing and encouraging the population of earthworms, bacteria, fungi, and the related assortment of soil microorganisms.

More Glues

Microbial polysaccharides are a glue secreted by a number of microbes, as a coating to protect them from desiccation (drying out). After the microbes die, the polysaccharides remain to help increase water-holding capacity of the soil. One notable microbial polysaccharide is xanthan gum, used to make many food products (such as ice cream) creamier and smoother in texture.

The strategy to improve microbe activity is almost identical to the methods of increasing earthworm activity: eliminate tillage, add cover crops or perennial crops, utilize high-protein residue and maintain surface residue, adjust pH to neutral with limestone (if necessary), and add manure or compost. This is discussed further in Chapter 5.

Humic acid and fulvic acid are the by-products of the decay of plant tissues (although some soil scientists are now challenging this view). They not only aid in aggregate stability, they also have a number of other beneficial functions, such as improved water-holding capacity and chelation of nutrients (holding them in a plant-available form). Humic and fulvic acids also possess a very high cation exchange capacity. Since these two compounds are by-products of microbial activity, the means to increasing them are exactly the same as for increasing microbial polysaccharides.

Humic acid and fulvic acid can be extracted from leonardite, a partially formed coal found in a layer just above coal. These are commercially available and highly effective as

fertilizer additives and as in-furrow applications to enhance seed germination.

Glomalin is the real star among the glues. Glomalin is unique because it is not only extremely effective as an aggregating agent but also is very stable and persistent in the soil, with an amazingly long half-life compared to most organic compounds in soil. It is also the compound that is most likely *not* being produced in a typical crop field. This is because it is produced only by an organism called mycorrhizal fungi that has been inadvertently eliminated from many of our crop fields due to tillage and fallow. Mycorrhizal fungi are beneficial fungi that live symbiotically on plant roots and aid the uptake of nutrients and water.

Increasing glomalin production is a little more involved than just repeating the steps for increasing earthworms or microbial activity. Since mycorrhizal fungi are most often absent in cropland, the process usually requires inoculation with spores of mycorrhizal fungi, and then managing the field to keep them alive. Mycorrhizal fungi are discussed at length in Chapter 5.

Finding Better Mucigel Producers

Some plants produce more, and better, mucigel than others. A couple of plants known to produce copious amounts of the stuff are mesquite and honey locust trees.

This may explain why these two trees tend to thrive in much drier environments than many other trees. Mucigel seems to aid the plant in water uptake, and it seems to add to the water-holding ability of the soil. Grass seems to grow much more profusely near the base of honey locust trees in pastures. (Part of this may be because honey locust trees are a legume, but whether or not they actually fix nitrogen is not entirely clear.)

After a honey locust tree is cut down, the area occupied by the root zone grows tremendous pasture. The thorny nature of wild honey locust trees makes them a nuisance, but perhaps they play a role in soil productivity that we do not fully understand.

Virtually no one wants to plant mesquites or locusts as soil improvement crops—at least at this time—but there are likely many other plants that perform a similar function. Grasses in particular can be quite effective at improving aggregation. Annual ryegrass, cereal rye, and Sudan grass are some of the better annual grasses, while almost all the perennial grasses dramatically improve aggregation.

CHAPTER 3 SUMMARY

Plant roots require three soil conditions for optimal growth: water, mineral nutrients, and oxygen. The least appreciated of these is oxygen.

- Oxygen availability to plants comes largely as a result of pore spaces with a connection to the soil surface. Tillage can temporarily increase soil pore space and oxygenation, but long term, it reduces soil oxygen content.
- Most management of soil oxygen involves reversing the damage done by long-term tillage and reestablishing stable soil aggregates. These practices encourage soil organisms to produce the biological glues that hold the aggregates together. They also allow larger organisms to form stable passages, such as root channels and earthworm burrows, in the soil profile.
- Soils saturated with water can soon become anaerobic, so subsurface drainage to remove excess soil water can allow oxygen to penetrate into otherwise anaerobic soil.
- Soil compaction can cause a lack of soil oxygenation, so means of preventing soil compaction such as reduced tillage, controlled and limited vehicle traffic, reduction in

equipment weight, maintaining a layer of surface residue, and cover crops can help soil oxygenation.

In summary, the desired soil structure we seek can be accomplished by elimination of tillage, ensuring high levels of available calcium, addition of manure or compost, maintaining surface residue, maintaining living roots as long as possible, producing high-protein residue, extending the period of photosynthetic activity, and inoculation with mycorrhizal fungi.

A Closer Look at Soil

The Human Impact

ABOVE: **FIGURE 1.1** *Like this cornfield, our agricultural fields are almost always monocultures, which are exceptionally susceptible to disease and insects. (See here.)*

ABOVE: **FIGURE 1.2** *Natural ecosystems, such as this prairie, are almost always polycultures. They are very resilient to climatic extremes as well as resistant to most plant diseases and insect pests. (See here.)*

ABOVE: **FIGURE 1.3** *In Providence Canyon State Park in the state of Georgia, this area is a* manmade canyon. *It was a forest until it was cleared for cotton farming in the 1830s. All of this soil erosion has occurred in fewer than 200 years. (See* here.*)*

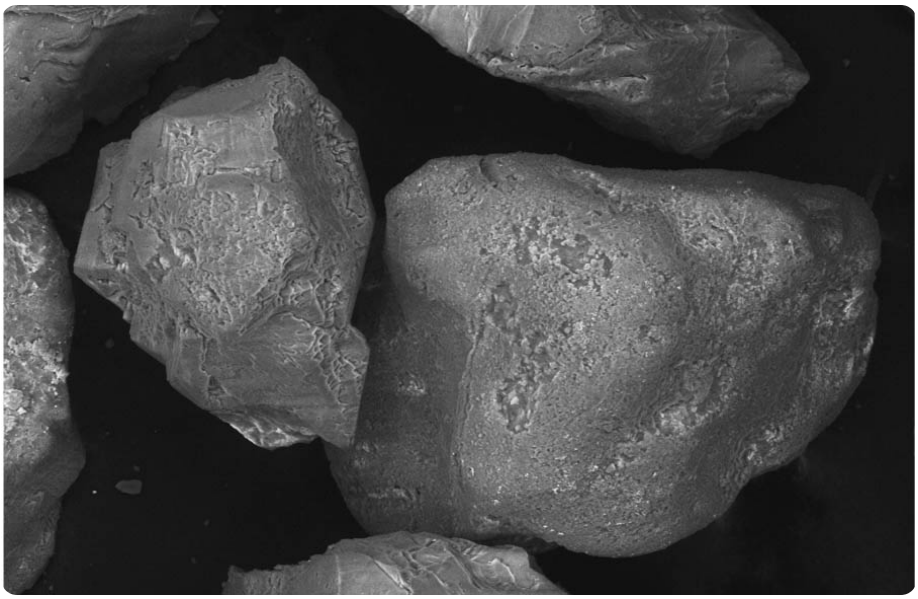
ABOVE: **FIGURE 1.4** *This phosphate mine is one of the few places in the world where phosphate rock (the raw material for making phosphate fertilizer) exists in minable quantities. What happens to our food supply when this limited resource runs out? (See here.)*

ABOVE: **FIGURE 1.5** *Algal blooms in lakes and ponds result from fertilizer runoff and can cause fish kills and toxic water. (See here.)*

Soil Composition

ABOVE: **FIGURE 2.1** *Corn (*Zea mays*) seedlings emerge next to plants in an established prairie, which is mostly eastern gamagrass, a close relative of corn. Note the far more abundant biomass in the established perennials, due to the head start they enjoy every year, while the annuals have to start from seed. How much more belowground biomass do the perennials have at this stage? (See* here*.)*

ABOVE: **FIGURE 2.2** *Clay particles are flat sheets, like pages in a book, and offer an incredible amount of surface area, but are not conducive to the passage of air or water between the particles. Water and nutrients are held in between the layers of clay, but air has a hard time passing through the sheets. (See here.)*



ABOVE: **FIGURE 2.3** *Sand offers very little surface area for holding water or nutrients but has large pore spaces for easy movement of air and water into the soil. (See* here*.)*

ABOVE: **FIGURE 2.4** *Soil with a platy structure, which might be caused by heavy traffic or tillage, can act as a barrier to movement of water and air into the soil. (See* here*.)*

ABOVE: **FIGURE 2.5** *Red subsoil (like the soil core from an unplowed area, left) shows high oxygen levels. Gray soil (like the core from the tilled area, right) shows low oxygen levels. (See here.)*

Soil Life

ABOVE: **FIGURE 3.1** *Dung beetles can quickly bury a cowpie, as shown here, much to the benefit of the pasture and any grazing animals. (See here.)*

ABOVE: **FIGURE 3.2** *Earthworms improve soil aeration through their tunneling activity, and they improve soil fertility through the deposition of their feces. (See here.)*

ABOVE: **FIGURE 3.3** *Mycorrhizal fungi colonize plant roots, living partially inside the plant roots and extending hyphae out into the soil well beyond the root system to help plants access water and nutrients. (See* here*.)*

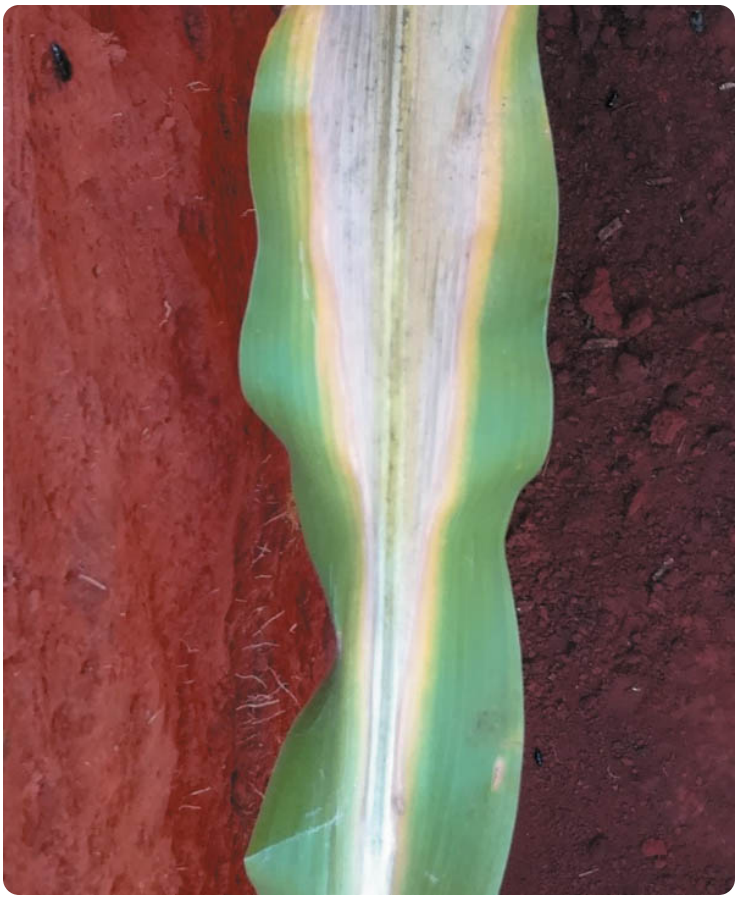
5YR NO-TILL 3YR COVERS
1YR MINIMUM TILAGE & COVER
1YR STRIP TILL COCKTAIL COVER FOLLOWING SMALL GRAIN (3RD CROP ROTATION)
CONVENTIONAL TILLAGE
2018
I SOILED MY UNDIES

ABOVE: **FIGURE 3.4** *The "I Soiled My Undies" test is a crude indicator of soil biological activity. Cotton briefs are buried in different soils for roughly a month. The more active the soil biology, the more decayed the briefs will be. (See* here*.)*

ABOVE: **FIGURE 3.5** *This soil in western Kansas has a dysfunctional water cycle from long-term tillage. It rained more than an inch here ten days before this photo was taken. Poor infiltration caused the water to run off and form the puddle to the left, not soaking into the soil. This area was thus too wet to plant.*

The soil to the right was planted to wheat, and the wheat seed is lying in dust, unable to sprout until the next rain. Did we learn nothing from the Dust Bowl? (See here.)

Mineral Deficiencies



ABOVE: *nitrogen*

FIGURE 4.1 *A nitrogen deficiency shows up as a yellowing on the lower leaves, beginning at the leaf tip and progressing back toward the stem, initially along the midrib and then widening. (See* here*.)*

ABOVE: *phosphorus*

FIGURE 4.2 *A phosphorus deficiency shows up as a purpling of the lower leaves. Cold temperatures and herbicide carryover can also cause purpling, but those usually affect all leaves, not just the lower ones. (See* here*.)*

ABOVE: *potassium*

FIGURE 4.3 *A potassium deficiency shows up as a burning of the lower leaf edges. (See* here*.)*

ABOVE: *Sulfur*

FIGURE 4.4 *Sulfur deficiency shows up as a general yellowing of the younger leaves and occurs most often on sandy, low organic matter soils. (See* here*.)*

ABOVE: *Iron*

FIGURE 4.5 *Iron deficiency shows up as a yellowing of the leaf area between veins on the younger leaves, while the veins themselves remain green. It usually occurs on soil high in powdered limestone. (See* here*.)*

ABOVE: *magnesium*

FIGURE 4.6 *A magnesium deficiency shows up as a yellowing of the area between the leaf veins, occurring on the older leaves. (See* here*.)*

ABOVE: *zinc*

FIGURE 4.7 *A zinc deficiency occurs as white or light purple stripes on the upper leaves. (See here.)*

ABOVE: *Manganese*

FIGURE 4.8 *Manganese deficiency looks much like iron deficiency but most often occurs in crops that are genetically engineered to be tolerant to the herbicide glyphosate. (See here.)*

ABOVE: *Boron*

FIGURE 4.9 *Boron deficiency can result in thickened and wilted leaves, failure of pollination, and internal rotting of roots and stems. It occurs most frequently on legume crops grown on sandy soils. (See here.)*

Soil-Restoring Solutions

ABOVE: **FIGURE 5.1** *In this composting technique, a Johnson-Su bioreactor relies on these aeration tubes to ensure aeration, rather than frequent turning as occurs in most composting methods. This lack of mechanical disturbance allows for fungi to proliferate.*

A finished Johnson-Su style compost will have a very high population of fungal spores. (See here*.)*

ABOVE: **FIGURE 5.2** *A particularly valuable soil amendment, biochar is charcoal that is infused with water, plant nutrients, and beneficial microbes. (See here.)*

ABOVE: **FIGURE 5.3** *Kelp is a source of many trace minerals and beneficial hormones that promote plant growth. (See here.)*

ABOVE: **FIGURE 5.4** *The casts (feces) of earthworms contain not only high levels of mineral nutrients, but also beneficial microbes, enzymes, and hormones that encourage plant growth. (See* here*.)*

ABOVE: **FIGURE 5.5** *The mycorrhizal fungi shown colonizing the roots above can extend well beyond the root zone and extract water and mineral nutrients otherwise inaccessible to the plants themselves. (See* here*.)*

ABOVE: **FIGURE 5.6** *A lithotrophic fungus can eat through rock and create soil. (See here.)*

ABOVE: **FIGURE 5.7** *Prairie fires reduce brush encroachment and stimulate herbaceous vegetation. (See here.)*

No-Till Implements

The right implements, designed specifically for no-till practices, will make the entire process more efficient and more effective.

ABOVE: **FIGURE 6.1** *Row cleaner (See here.)*

ABOVE: **FIGURE 6.2** *John Deere opener (See here.)*

ABOVE: **FIGURE 6.3** *Great Plains opener (See here.)*

ABOVE: **FIGURE 6.4** *Keeton seed firmer (See here.)*

ABOVE: **FIGURE 6.5** *Seed firming wheel (See here.)*

ABOVE: **FIGURE 7.1** *Press wheel (See here.)*

ABOVE: **FIGURE 7.2** *Thompson closing wheel (See here.)*

ABOVE: **FIGURE 7.3** *Roller-crimper (See here.)*

Crop Rotation

ABOVE: **FIGURE 8.1** *A field in a corn–soybean rotation. Next year corn will grow where the soybeans are in the photo, and soybeans where the corn is. (See here.)*

ABOVE: **FIGURE 8.2** *Including a pastured forage crop in the rotation can provide tremendous soil health benefits in a short period of time. (See here.)*

04

Water

According to data from the United Nations, approximately 41 percent of the world's land surface is considered "dryland," meaning that rainfall on an annual average basis is insufficient for optimal crop yields. According to every farmer I have ever met, 100 percent of his or her farm is in the most inhospitable desert on Earth, and it never rains when they need it to.

In reality, the central issue is not just how much rain you get. It is also about how well you set up your soil to utilize rainfall. This chapter will deal primarily with methods for managing soil to deal with limited rainfall. Perhaps ironically, these same measures are also very helpful in dealing with an excess of water, also known as flooding.

Dust to Mud and Back

I get calls from guys in the US state of Georgia, and they tell me how dry it gets around them—mind you, they average 50 inches of rain per year in Georgia, which is twice what my farm averages, but that is a moot point. If you are used to 25 inches and receive 25 that is normal. If you live where you average 50 and receive 25, that is a disaster.

Many of the normally wetter areas, especially in the southeastern US, have soils with either very poor infiltration rates or very poor water-holding capacity, or both; therefore, they need frequent rain. Also, average rainfall is calculated into land prices and rental rates. I heard a farmer from Iowa talk about giving a speech in Texas. One of the audience members stood up and growled at him, “You make me sick. Farming is easy where you are. You have good soils and good rain. You would never survive here.” To which the Iowan responded, “Yes, we do have good soils and good rain. But we also have cash rent values of $500 an acre. Could you survive that?”

The point is, farming is tough everywhere, and when rain does not fall when you need it, it is tougher yet. Even a tiny hiccup

creates havoc when you have a $500-an-acre cash rent payment to cover. It is also tough when too much rain falls. When rainfall is excessive for a period of time, it can be hard to get any field work done, it can delay planting and delay harvest, and it can make life on the land miserable and difficult. When rainfall is very excessive, flooding can wipe out a year's income in one event, even destroy homes and buildings accumulated over generations. It seems there is always either too much or too little water.

Too Much or Too Little

Too little water for too long is called a drought. Droughts have caused enormous suffering throughout history, primarily through starvation, and have even caused the collapse of several civilizations. We blame droughts on the lack of rainfall, but so much of the impact of less than optimum rainfall can be minimized through better soil management. It was the drought of 2012 that sparked me to write my first book, *The Drought-Resilient Farm*, after I observed huge differences in crop yields in side-by-side fields with different soil management. In adjacent fields, there were crop failures and crops that were quite close to normal yields for the area.

The opposite of a drought is, of course, a flood, which is too much water in too short a time. Floods cause more economic damage than any other form of natural disaster. As I write this book, we are just coming out of a winter in which a "Bomb Cyclone" poured massive amounts of rain on already saturated and frozen soils over much of northern Nebraska and southern South Dakota. This combination caused massive flooding across the area and transported enormous ice sheets as much as 15 feet thick for miles down rivers, where they landed in downstream

fields and cities. This disaster wiped out homes that had stood for more than a century and caused massive economic damage over a huge area.

The circumstances that coincided to contribute to this historic level of flooding in this instance were not necessarily caused by human mismanagement (this time); they were just an unfortunate coincidence of weather events, with unusually heavy winter rains falling on soil that was both saturated and frozen. However, this tragic event should serve as a warning, because on most of the world's cropland we are managing soils in a manner that could cause this sort of event to become more and more frequent over time.

In order to manage water, however, we must first understand the water cycle.

The Water Cycle

Precipitation forms in the atmosphere when water vapor cools and condenses around particles called condensation nuclei. These little balls of water float in the atmosphere and gather in clouds, until enough of them coalesce together into ever-larger droplets that finally become heavy enough to fall. When the water drops to the earth, it can do so as liquid water (rain, drizzle) or as solid water (snow, hail, sleet).

When the water hits the land surface, either it can enter into the soil (infiltrate) or it can move off the land surface downhill (run off). The water that penetrates the soil may remain in the soil profile or, if enough water enters the soil profile, it may move downward past the root zone (leaching) and enter into underground deposits of water (groundwater).

Large deposits of groundwater are referred to as aquifers. The water that remains in the soil profile may become warm enough that it converts back to water vapor and returns into the atmosphere; this is called evaporation.

The soil moisture may also be taken up by plants. A small portion of this water (2 to 3 percent) is used by plants in photosynthesis; the rest moves through the plant and exits through little holes in the leaves called stomata. This process is called transpiration. Evaporation and transpiration together move water vapor back into the atmosphere.

What We Can Do about the Weather

What if we could do something about the weather? Or more precisely, what if we could make it rain more in drier areas? Sound preposterous? For millennia, people have tried to make it rain through everything from rain dances and sacrifices to the gods to rockets shot into the clouds—you name it, it has been tried. Even in the modern era, we have used our knowledge of the science of meteorology in attempts to seed clouds (with silver iodide crystals, spread from an airplane, serving as condensation nuclei) to induce a drought-breaking rain, and we have done this with some success.

Everybody Complains about the Weather, but Nobody Does Anything about It

For years, my grandfather (on my mother's side) had a good friend named Vernon who lived two miles down the road from him. Every time it rained in the summer, Grandpa would drive over to Vernon's house to see how much rain he got. And every time, Grandpa came back mad as a hornet. "I swear, that Vernon is the luckiest farmer around. I don't know why, but it always rains more over there on his place than it does here," he would say, stomping around, angry that the luck of the Irish never seemed to apply to this little Irishman.

I saw Vernon one day after my grandpa passed. We talked about Grandpa a bit, and Vernon said, "You know, I got the biggest kick out of your grandpa. Every time it would rain, I knew he would be coming over, so I would run out to the rain gauge before he got here and add a little more water to it. Then when he arrived, we would go check the rain gauge together. He never did catch on!"

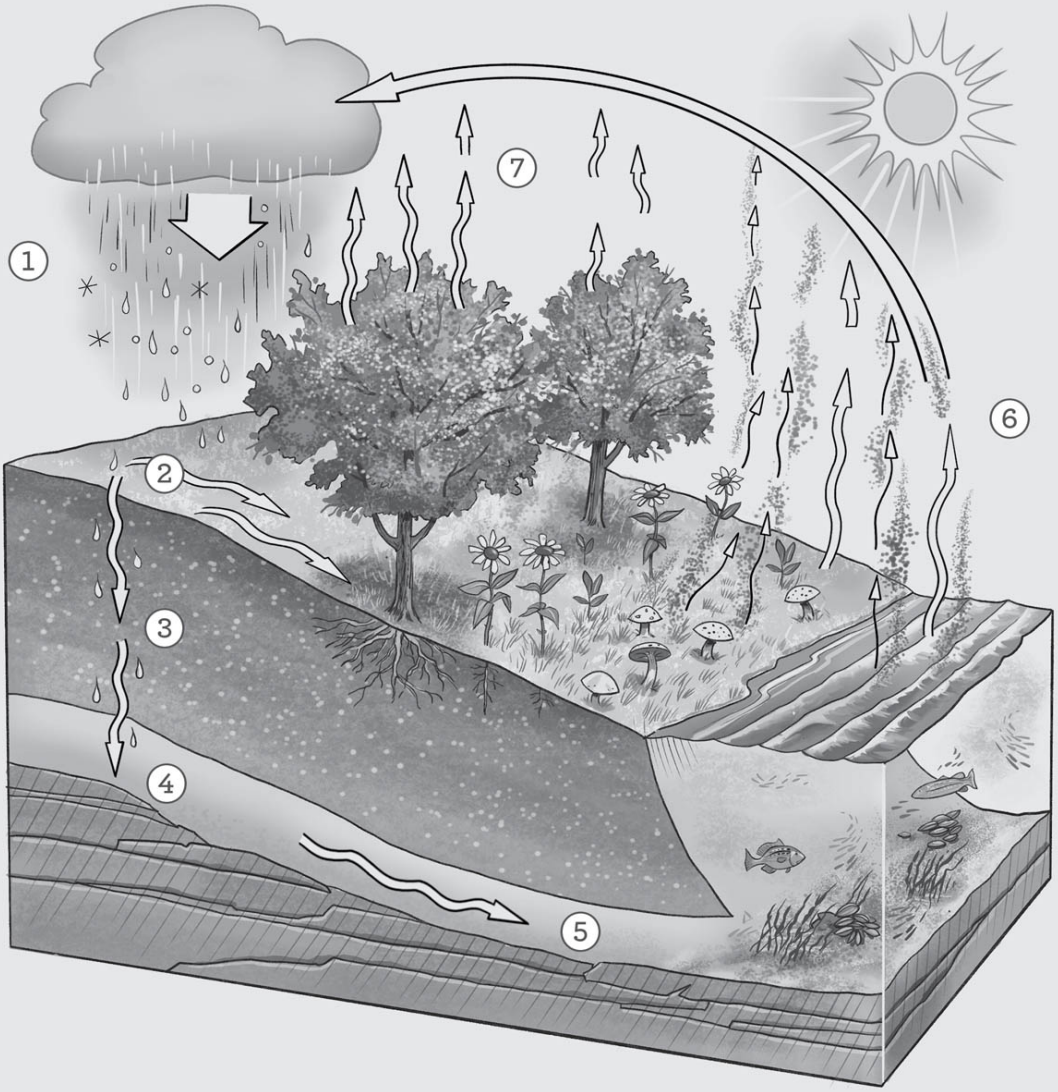
As it turns out, however, we as a species may actually have been controlling the weather for centuries, but not in the way we thought.

As the science of weather events expands, we have learned more and more about why it rains or does not rain. One discovery involved which particles are effective condensation nuclei and which are not. I was taught in school that condensation nuclei are specks of dust, small particles of soil. Large amounts of dust in the air are caused by widespread areas of tilled cropland that are left bare and fallow.

It turns out, however, that these particles are actually rather poor condensation nuclei. They need a lot of moisture in the air to

make it rain, much more than other, more effective condensation nuclei do. Because it takes a large amount of moisture buildup to trigger the rain, the precipitation events that occur when dust is the primary condensation nuclei are infrequent. And the rain is very intense because of the volume of moisture required. In other words, tillage and fallow precipitate a cycle of alternating drought and flood.

WATER CYCLE



ABOVE:

1. Precipitation: rain, snow, sleet, hail, fog, dew, etc.
2. Runoff of rainfall
3. Infiltration of rainfall into soil
4. Percolation of soil water into groundwater
5. Groundwater

6. Evaporation from soil or water surface
7. Transpiration from plant leaves

We as a species may actually have been controlling the weather for centuries, but not in the way we thought.

BEST "RAIN SEEDS"

The most effective condensation nuclei appear to be the following:

- microbial bodies (bacteria) that originate on leaf surfaces
- fungal spores that primarily originate from mushrooms
- volatile organic compounds produced by aromatic tree leaves such as pines
- compounds produced by oceanic plankton called dimethyl sulfides

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The **fungal spores** are particularly interesting. The spores coat themselves with a sugar called mannitol that is very **hygroscopic**, which means it draws moisture from the air to attach to the spore. This makes the spore heavier and bends the little stalk that it is attached to. Then it is launched as if from a catapult into the air, with a force an incredible 25,000 times the force of gravity, or 1,000 times the force the Space Shuttle generates. This propels the spores into the air so they can blow in the wind and end up eventually in a cloud. The hygroscopic sugar makes these spores very effective condensation nuclei.

The bacteria that originate on leaf surfaces are likewise effective at lower amounts of moisture; so effective, in fact, that bacteria have been used as the condensation nuclei for making artificial snow at ski resorts for about 60 years now. The microbes originate from green plant leaves and fungal spores (from mushrooms) that live on plant residue on the soil surface. While the idea is certainly interesting, what is even more exciting is how we can use the information to change our weather patterns.

Biologically derived condensation nuclei produce a desirable rainfall pattern that tends to be much gentler and more frequent than rain caused by soil particles. As noted, soil particles as condensation nuclei result in an undesirable rain pattern that is infrequent and intense. If rain is frequent, there are no droughts; if rain is gentle, there are no floods.

Therefore, it stands to reason that replacing large areas of tilled and fallowed cropland with no-tilled fields (with residue left on the surface to feed mushrooms) that are covered with green leafy cover crops would make more of the frequent and gentle rain we want instead of long periods of drought interrupted by “toad-drowner” rains. Alternatively, if we were to replace cropland with prairies and forests, perhaps we could stabilize precipitation even more effectively.

Bacteria and Natural Rainfall

This is not a very recent discovery, but for some reason not many people have connected the dots to bacteria and natural rainfall.

Dave Sands, a plant pathologist at Montana State University, made this link as far back as 1978 and referred to fungal spores creating rain as "bioprecipitation." He linked it to increased risk of wheat diseases because the fungal spores he was studying were indeed spores of pathogenic fungi that attacked wheat.

In 2008 Brent Christner of Louisiana State made a similar connection in regard to the microbes on leaf surfaces. This idea of rain being biologically induced once seemed pretty far-fetched but is now becoming mainstream. The January 2009 issue of *National Geographic* ran an article on the topic called "Rainmaking Bacteria Ride Clouds to Colonize Earth."

When It Rains, It Pours

Another way we have unintentionally contributed to the cycle of droughts punctuated by floods caused by bare soil is something called the "flywheel effect" of soil moisture. This phenomenon is being studied by NASA in what is called the Soil Moisture Active Passive (SMAP) project. When rain falls on bare, tilled soil, most of that moisture will remain at or near the soil surface (due to poor infiltration) and will rapidly evaporate back into the air, where it can cause rain again in short order. Thus, a gully-washer rain is quite often followed by another gully-washer rain. Bare soil creates this cycle, and once it rains big, it will keep raining big for a while.

In contrast, with soil covered by vegetation, a higher percentage of that moisture penetrates deep into the soil due to better infiltration, and less of it will evaporate over the next few

days. Instead, that moisture will be transpired from the leaves of the growing plants over the course of several weeks, leading to more of an extended period of small frequent rains. Once again, green growing plants provide the solution.

But wait! There's more! (If you order before midnight tonight . . .)

Green Growing Power

It's obvious that green growing plants contribute to atmospheric moisture both with the microbes that originate from their leaf surfaces and from transpiration. But just how much they contribute has surprised even scientists. Human activities have changed weather patterns from what they were historically, particularly over North America. The observation that trees make rain has been called the "green pump" effect, and on islands that have been totally deforested, the climate has become much drier.

On the other side of the coin, it has been observed that the increase of corn irrigated by center pivots over the Ogallala Aquifer region of the plains area of eastern Colorado, western Kansas, and much of Nebraska has made it rain more in the summer in the area northeast of there (downwind from the prevailing southwest summer wind). What would happen if the areas now growing continuous winter wheat and left bare all summer were to have a green growing cover crop in them? There are some researchers examining the effect of cover-cropping land with green plants for the entire growing season and comprising a wide geographical area, and they are finding that indeed they do increase rainfall in areas that are downwind.

Climate Change and the Roles Played by Plants and Soil Organic Matter

A growing number of researchers believe that the water cycle, not atmospheric CO_2, is the main driver behind climate change. Major proponents of this theory are Michal Kravčík, Jan Pokorný, Juraj Kohutiar, Martin Kováč, and Eugen Tóth—Slovakian and Czech scientists and researchers and coauthors of the scientific paper "Water for the Recovery of the Climate: A New Water Paradigm." The authors state that the lack of soil moisture around the world due to poor soil function is leading to land areas heating up because they no longer are cooled by the transpiration of green plants.

This sentiment is echoed by Spanish meteorologist Millán Millán, who has studied the effect on regional rainfall of deforestation and agriculture based on tillage. The idea is that if we simply revegetate large areas now tilled and left fallow, the cooling effect of transpiration will prevent global warming.

In addition, the improvement in rainfall infiltration and the increase in water-holding capacity from increased soil organic matter will keep more water on the landscape and out of the ocean. An extra inch of moisture on the world's land area adds a lot of moisture to the air over time, while an extra inch of moisture on top of the world's oceans contributes no more to the atmospheric water supply than the ocean below that inch would have. The key to maintaining a cooler world

climate, according to these researchers, is keeping more water on the landscape for a longer period of time.

Of course, ideas on paper are just ideas on paper, yet there are examples of regreening projects that have accomplished amazing things. One such project was started over 30 years ago by a man in India named Rajendra Singh. He began by encouraging construction of water catchment areas, which collected enough to revegetate parts of the Thar Desert, with around 7 inches of annual rainfall. The result has been an increase in food security for 1,200 villages, and rivers that were formerly dry are now flowing again in a slow, sustained manner. The bottom line is that these ideas work, at least on a local level. If they also contribute on a global scale, so much the better.

Greening a Desert

THE AL BAYDHA PROJECT, Hijaz Mountains, Saudi Arabia

If you took a million farmers and placed them on a field of nearly pure rock in a hot desert with a 2-inch annual rainfall and asked for their recommendations, I imagine 99.999 percent would simply say: "Move." How could you grow anything in such conditions? Read on and discover how, with ingenuity and hard work, that 0.001 percent who refuse to say "impossible" discovered how to make plants grow in one of the harshest environments on Earth. If it can be done there, it can be done anywhere.

In 2009 a pilot project was undertaken to restore a desert region in western Saudi Arabia, about 50 kilometers south of Mecca, in the Hijaz Mountains. The region is very arid, averaging only 2 inches of rain a year, the soil is quite rocky, and the area is stricken with extreme poverty. The inhabitants are primarily Bedouin shepherds who supplement their meager income by cutting trees and selling them for charcoal production in Mecca. As the trees have been cut down over the years, there has been a loss of feed for their animals, and clearly the trees are not growing fast enough to sustain the level of cutting.

The Al Baydha Project was a collaboration between Her Royal Highness Princess Haifa Al Faisal, Mona Hamdy of Harvard, and Neal Spackman of Stanford. The goal was to

develop a landscape that could provide a sustainable local economy yet maintain the pastoral culture, turning a local problem into an asset.

Rainfall is infrequent but very intense when it does occur. Flash floods are dangerous: The rocky soil and steep topography contribute to rapid water runoff and massive erosion. The idea was to put in place water-harvesting structures similar to a Keyline system, but with the rocky soil a subsoiler or any landmoving would be very impractical.

An alternative idea, however, was to construct rock terraces along the same contour lines as might be used in a Keyline system, to plot out a path for a Yeoman chisel plow across the sloping uplands. Next the team built small check dams across temporary watercourses to slow the flow of water and gently divert it onto adjacent areas, spreading it across the landscape. Once the contour rock dams and check dams accumulated some sediment, farmers planted drought-tolerant, fodder-producing trees for livestock browse. Forest regeneration with native acacias is also becoming evident.

To provide the people with an income source other than firewood, a dairy-processing industry was also established to market the excellent cheese and butter (for which the Bedouins are locally famous) in nearby Mecca. The project is beginning to pay dividends.

This project shows how we can successfully rehabilitate and improve land on some of the worst soil in one of the hottest, driest climates on the planet. By trapping sediment, accumulating it above the rock terraces, and preventing its loss downhill, and by similarly capturing runoff in the sediment above the rock terraces, rather than letting it fall to

the streambed below, we can make things grow on extremely limited rainfall.

If you would like to learn more about the Al Baydha Project, see For Further Reference.

How to Improve the Water Cycle

In most nonirrigated cropping situations, lack of adequate soil moisture is the most common limiting factor to crop growth. Quite often, there are soil moisture deficits even when total annual rainfall should be more than adequate.

A prime example is the area in which I was raised, southeastern Kansas, where the average annual rainfall at the time was about 36 inches per year. To put this into perspective, it takes about 24 inches of soil moisture to raise a 200-bushel-per-acre corn crop. Yet we struggled to get 100 bushels of corn per acre, achieving this feat only a few times during my childhood, despite receiving in an average year 50 percent more rain than what is needed for a 200-bushel yield.

I was told it just didn't rain enough, and from the burned appearance of our corn in most years, that certainly seemed correct. But when I went to college, I made friends from western Kansas who raised better corn than we did on a little more than half our rainfall.

Clearly, the amount of rain received was not nearly as important as the amount of rain that actually went into the soil and was stored there. Our heavy clay soils had subsoil infiltration rates of 0.02 inches per hour. If you do the math, that means it

took over two days for an inch of moisture to soak into the ground. If rain fell faster than an inch in two days, which it always did, a good chunk of that rainfall simply ran off the surface and down to the nearest pond. Only a small fraction of our 36 inches of annual rainfall actually made it into our soil.

Here are some recommended steps.

STEP 1: Increase Infiltration of Rainfall.

The first and most important step in improving the moisture-supplying ability of soil is to ensure that any rainfall received makes it into the soil instead of running off. Increasing surface soil infiltration rates should be a primary goal of soil management in areas where a lack of rainfall limits crop production. The following are some techniques for improving rainfall infiltration.

- **Stop tillage.** While one of the stated goals of tillage has historically been to create a loose soil condition so that rainfall can easily enter, in reality the exact opposite occurs. A tilled soil has its aggregates exposed to raindrop impact. This breaks the aggregates apart into small individual particles and forms a layer of closely packed fine soil particles that slow further movement of water into the soil profile. In addition, tillage oxidizes soil organic matter, further reducing the ability of soil aggregates to withstand raindrop impact (see the table).
- **Keep the soil surface covered.** Preventing raindrop impact from destroying soil aggregates and creating a crust can be accomplished by "armoring" the soil with a protective layer of plant material. This can be dead plant material, such as residue from the previous crop, or live plant material from a cash crop or cover crop. Crop residue should not be tilled under or

harvested, and cover crops should be planted whenever there is no cash crop growing. Pastures should never be grazed to the point in which bare soil is exposed to raindrop impact.

- **Add cover crops to the crop rotation.** Cover crops can greatly increase the rate of water infiltration. Part of the benefit comes from their contribution to soil surface coverage, and some comes merely from friction that slows overland waterflow as it moves through the plant material. But there are other contributions as well, such as providing root channels and feeding soil organisms such as earthworms that create macropores in the soil. Perhaps the biggest benefit of cover crops may be the production of root exudates that feed the soil microbes that cause soil aggregation.
- **Include perennial forage crops in the crop rotation,** or permanently plant land to perennial vegetation. These forages have a highly beneficial effect on soil aggregation and provide consistent soil coverage with residue and growing plant material. (See Figure 2.1.)
- **Add organic mulches to the soil surface.** Mulch materials can be wood chips, straw, compost, manure, or any other coarse plant- or animal-derived material. Mulch improves the infiltration of rainfall and also reduces the loss of water from evaporation.

What Does NOT Work to Increase Water Infiltration

One of the many strategies for increasing water infiltration is called subsoiling. Research indicates that while subsoiling is highly effective at increasing water infiltration, those benefits

are lost if any secondary tillage is performed after the subsoiling. The data also show that the infiltration rate of the subsoiled area followed by secondary tillage was worse than the infiltration in other areas. On cropland, subsoiling usually leaves the soil surface rough and cloddy, and secondary tillage is performed to level the field to prepare for planting. Driving on a field with heavy equipment after a subsoiling operation will likewise eliminate the benefit of subsoiling.

For subsoiling to be effective at increasing water infiltration, the following conditions must be met:

1. The subsoiled area must not be driven on or tilled after it is subsoiled; obviously, this precludes planting anything after the subsoiling operation as well.
2. The channels created by the subsoiler must remain open to the soil surface, so it is imperative that the soil has sufficient structural stability to not melt away and fill in the channels after a rain.

Because it is difficult to meet these two conditions on annually cropped land, subsoiling might best be reserved for land growing established perennial vegetation of a rhizomatous or stoloniferous nature, such as a pasture of bermudagrass, buffalograss, reed canarygrass, smooth bromegrass, western wheatgrass, Kura clover, or white clover.

These plants have strong root systems that regrow rapidly along the sides of the channels. This helps to hold the soil intact and prevent the channels from filling in due to soil slumping off the sides of the channels during wet conditions.

It also provides coverage of the soil surface to prevent soil erosion and keep the channels from filling in with sediment washed downhill after a rain. In addition, these plants can grow deep roots in response to the increased oxygen supply created by the channels to fully exploit and maintain the channels' effect.

Subsoiling can be used after the establishment of a temporary sod used in a crop rotation, or in permanent pastures, especially pastures that are being treated by the Keyline method, as discussed later in this chapter.

STEP 2: Increase Soil Water-Holding Capacity.

Increasing soil water-holding capacity is the second step in improving the soil's ability to supply moisture to plants. And the best way to improve soil water-holding capacity is to increase soil organic matter. A partial list of methods to increase soil organic matter include:

- **Elimination of tillage.** Tillage oxidizes and reduces soil organic matter, as discussed earlier in this book.
- **Retention of surface residue.** Crop residue that is removed from the field will not decompose into soil organic matter in the field.
- **Adding cover crops to a cash crop rotation.** Cover crops can increase soil organic matter content, particularly in conjunction with elimination of tillage.

- **Planting perennial forage crops on cropland.** Perennial forages will produce more organic matter in less time than any other measure, and much of this is due to having an established root system producing exudates every day of the year.
- **Incorporating livestock grazing into a crop rotation.** The manure from ruminant animals can create more soil organic matter than the decay of the plant material that the animal consumed to produce the manure.
- **Managing grazing** so that sufficient leaf area is always present to fully capture sunlight. An overgrazed pasture with sunlight striking bare ground will not produce as much organic matter as one with complete coverage of the soil surface with leaves (this is further discussed in Chapter 11).
- **Improving availability of mineral nutrients.** Any nutrient deficiency that limits plant productivity will reduce the plant biomass and amount of root exudates that can decay to form soil organic matter.

HOW NITROGEN FERTILITY AFFECTS SOIL ORGANIC MATTER

* Samples were taken at the end of the period.

SOURCE: K. McVay et al., "Management Effects on Soil Physical Properties in Long-term Tillage Studies in Kansas," *Soil Science Society of America Journal* 70, no. 3 (2006): 434–438.

HOW NITROGEN FERTILITY AFFECTS SOIL ORGANIC MATTER

LOCATION	NITROGEN FERTILIZER RATE	SOIL ORGANIC MATTER MG/HA	DURATION OF STUDY* (IN YEARS)
Hays	0	7.33	38
	67 kg/ha	8.37	
Manhattan	0	9.97	13
	High (rate not specified)	11.70	
	Manure to equal N rate of high N	13.35	
Parsons	0	9.04	20
	40 kg/ha	9.56	

* Samples were taken at the end of the period.

SOURCE: K. McVay et al., "Management Effects on Soil Physical Properties in Long-term Tillage Studies in Kansas," *Soil Science Society of America Journal* 70, no. 3 (2006): 434–438.

- **Maintaining living roots** for as much of the growing season as possible. Live roots produce root exudates to feed the soil microbes that produce organic matter, so the more days that roots produce exudates, the higher the level of soil organic matter.

- **Adding manures, composts, and other carbon-based fertilizer materials.** These materials will feed soil organisms that produce organic matter upon decay.
- **Increasing crop diversity.** Various plants produce root exudates that are high in sugar, or protein, or lipids, and some produce exudates that make minerals more available. When there is a diversity of root exudates, a more nutritious "soup" is formed to better nourish the soil microbes that form soil organic matter. For example, sorghum-sudangrass produces root exudates that are high in sugar, cowpeas produce exudates high in protein (amino acids), sunflowers produce root exudates high in lipids, and buckwheat produces root exudates that make phosphorus more available in the soil.

When all these plants are present together, the microbial population is much higher than when a pure stand of any one of these plant species covers the field.

STEP 3: Decrease Evaporation.

Decreasing evaporation is also a way to retain more moisture in a soil for plants. Methods of reducing evaporation include:

- **Retaining a mulch on the soil surface** by not harvesting or tilling crop residue, by growing cover crops to create additional mulch, or by importing mulch from external sources. Maintaining surface residue will reduce evaporation of soil moisture.
- **Reducing wind speed at the soil surface** through field windbreaks or by leaving tall stubble in the field.

STEP 4: Encourage Deeper Rooting of Your Crops.

As discussed earlier, root depth is limited by the penetration of soil oxygen into the soil. The flow of soil oxygen into the soil can be improved by improving soil aggregation and formation of soil macropores. This can be accomplished with these practices:

- **Eliminating tillage,** which destroys soil aggregates
- **Rotating with deep-rooted cover crops,** particularly those that grow deep roots during cooler periods when soil oxygen is higher
- **Adding carbon-based soil amendments** to feed the microbes that encourage soil aggregation
- **Maintaining living roots in the soil** for as much of the year as possible to feed root exudates to soil-aggregating organisms
- **Encouraging earthworm growth**
- **Grazing with livestock,** which encourages populations of soil-burrowing dung beetles
- **Inoculating with mycorrhizal fungi** if they are not already present in the soil (see full discussion in Chapter 5)

Landforming

My father was a big believer in terraces to control erosion and had a bulldozer and grader for their construction. I watched him build broadbase terraces on many occasions and wondered why the terraces were sloped downhill to conduct water off the field into a

grassed waterway. I asked why he built them this way, when nearly every year our crops suffered from lack of moisture. Wouldn't it be better to make the terraces level so that the water, instead of running off, would be stored for when he needed it later?

He explained that if we laid the terraces level, the standing water that would accumulate in them after our spring rains would either delay planting (if they occurred before we could plant) or drown out our crops (if the rains occurred after planting). That answer made complete sense to both of us at the time. Millions of miles of terraces have been built in this country in the same exact manner: to remove "excess" water from the field. The terraces were meant to control erosion, not act as an aid in enhancing soil moisture.

But what if our landforming practices were intended to do both?

Starting at the Roots

The root problem of both soil erosion and lack of soil moisture is a lack of water infiltration. In the conventionally tilled conditions during the 1970s and '80s (when these conditions were nearly universal), the soil could absorb rain only until the pulverized surface sealed off due to raindrop impact; then runoff began.

This meant that not only was there not enough moisture in the soil where the raindrops fell, but also that the runoff had to go somewhere. If it hit a terrace channel and accumulated, the accumulation became a problem when the water couldn't move into the soil.

Obviously, managing the soil so that runoff is minimized is the very first step in ensuring adequate soil moisture for crops, for

prevention of erosion, and for reducing downhill flooding and drowning of crops. The role of landforming, though, is to put inevitable runoff water to productive use, rather than treat it as a problem to be disposed of, as the majority of terraces in this country are designed to do.

Note: It's Not the Cheapest Way to Go

One important thing to remember about landforming is that it is usually quite expensive; it's one of the more expensive ways to control soil erosion or reduce water runoff. It is most profitably utilized in situations in which other means are already in place but have been found to be insufficient.

An Overview of Landforms

Terraces are a familiar type of landform, but there are numerous other options.

SWALES

A **swale** landform resembles a **broadbase terrace** (a terrace with a gentle enough slope that farm machinery can cross it), but it is designed to retain water rather than carry it off to a waterway.

A swale has two parts: a shallow, linear channel laid out on contour and a berm on the downhill side of the channel (formed from the excavated soil). A swale forms a temporary, shallow,

linear pond and holds the water there long enough for it to infiltrate the soil.

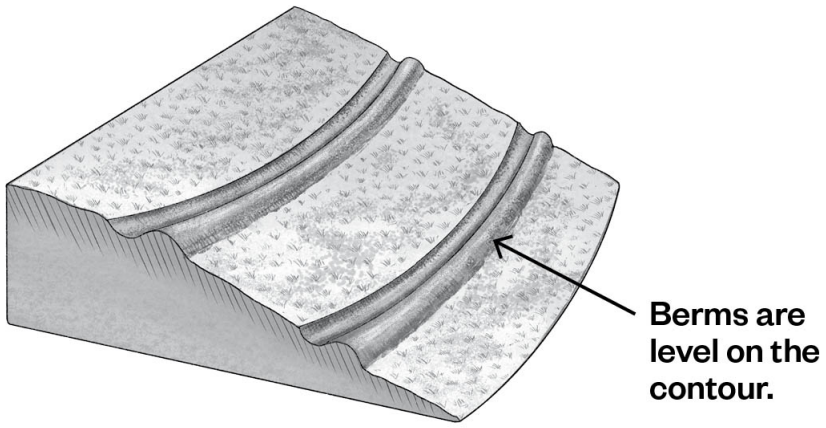
Since many crops do not tolerate standing water, plant the swale to flood-tolerant vegetation such as reed canarygrass or eastern gamagrass, two grass species also known for their ability to promote water infiltration and provide forage. Other water-tolerant vegetation includes willows or poplars, also useful as forage species. Apply a layer of mulch to the channel of the swale as an additional aid to infiltration.

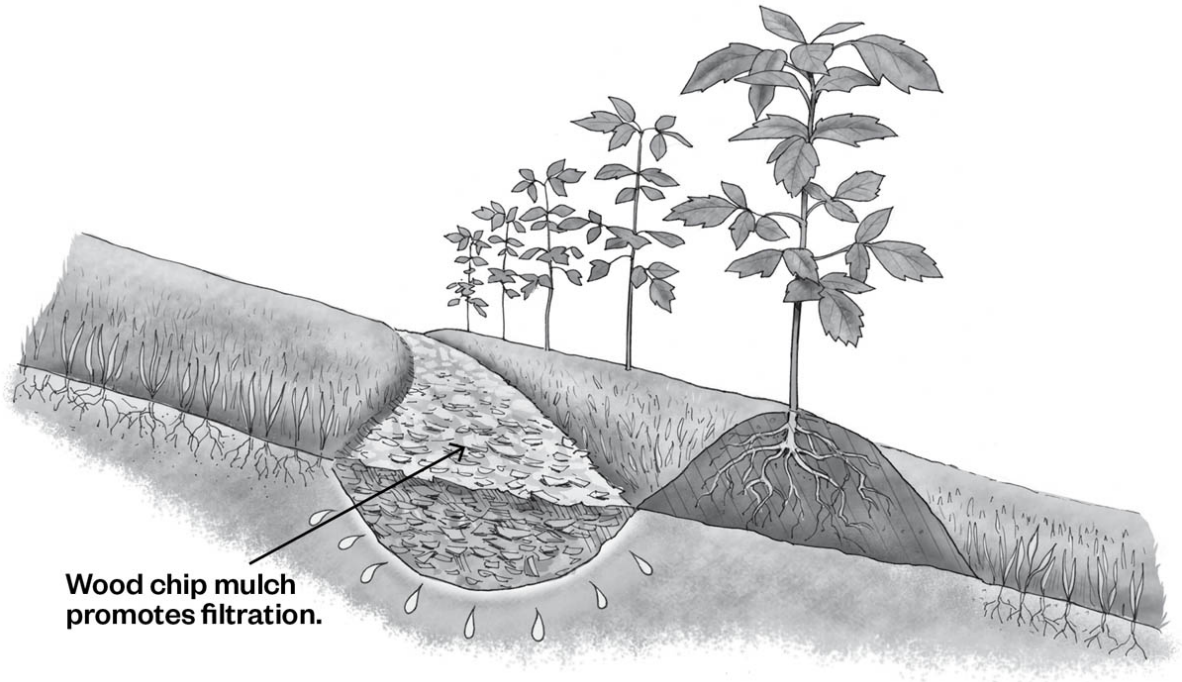
You can also put the berm to use and plant it to high-water-demand plants like fruit trees or nut trees. The berm's slight elevation provides excellent internal drainage while also receiving abundant soil moisture from water infiltrating below the channel. The infiltration from the swale increases the supply of moisture in the soil below it.

Swale

Both terraces and swales are berms of earth, formed to slow the downhill movement of water. A swale, however, is designed to capture and retain water rather than letting it slowly move downhill. This results in a series of long, linear, temporary ponds on the contour after each runoff event.

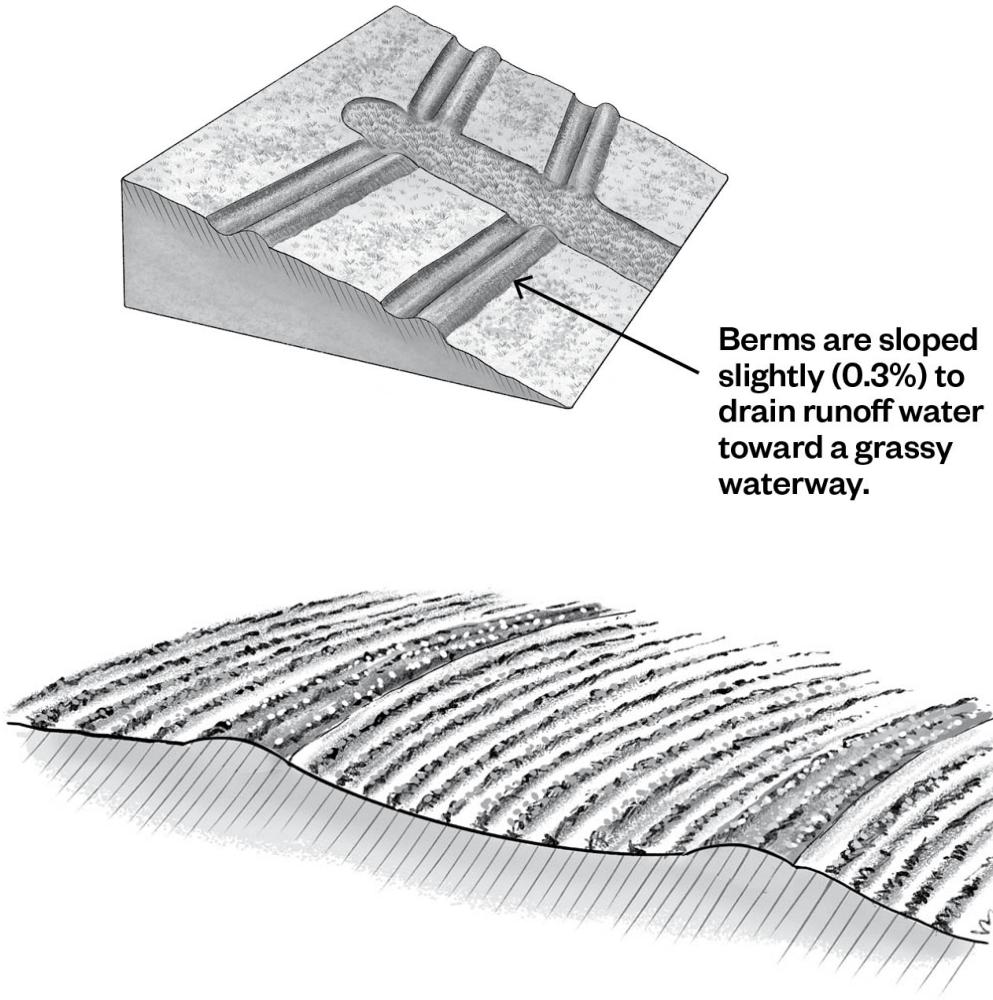
Terraces, as used in the US, are designed to convey water gently off a field without bringing soil along with it. Unlike a swale, which captures and holds water, a terrace is intended to minimize standing water, which could cause crop losses.


Berms are
level on the
contour.


Wood chip mulch
promotes filtration.

Terraces

A broadbase terrace is designed so that it can be crossed over with normal farm machinery and can itself be cropped; however, it is suited only for rather gentle slopes. Grass-backed terraces are suited for steeper slopes, breaking that incline into numerous level benches that are held in place with perennial grass.



ABOVE: *Broadbase terrace*

ABOVE: *Grass-backed terrace*

VERTICAL MULCH

Another approach to putting runoff water to productive use is the creation of a **vertical mulch**. A vertical mulch system is a series of narrow slits or trenches in the soil laid out on the contour, at fairly close spacing (often 6 feet between trenches) that is backfilled with organic material.

A vertical mulch is extremely useful in very heavy clay soils, for multiple reasons. Heavy clay soils suffer from poor water infiltration and poor rooting depth (due to poor oxygen infiltration) as well as from severe cracking under water stress that not only exposes more soil surface area to evaporation but can also actually tear roots apart. The trenches filled with loose porous material act as a passage for runoff water to enter the soil.

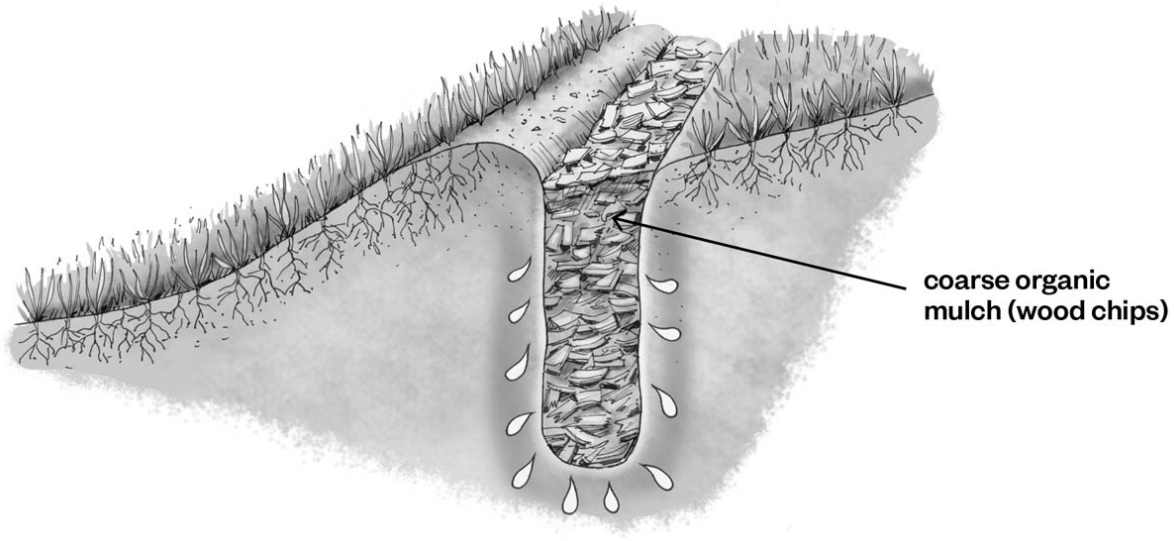
They also expose more soil surface area to oxygen to nourish deeper root growth.

Another bonus of vertical trenching is that the trenches provide designed places for cracking to occur, similar to the slits cut into a concrete sidewalk. An acquaintance who lives in an area of heavy clay, prone to cracking, has found that he can cut a slit with a coulter midway between his rows of corn planted on the contour, so that cracks in the soil appear midway between the rows instead of randomly, which helps minimize root damage to his crops.

The cracks also appear on the contour of the slope, so that they act as entry points for water the next time it rains. They also provide an opportunity to create a vertical mulch with relatively inexpensive and low power equipment; a person could just create the slits with a single coulter blade on the contour, wait for dry weather to form the cracks along the slits, then spread organic matter with a manure spreader, and the next rain washes the organic material into the cracks.

Vertical Mulch

A vertical mulch is a narrow trench, placed on the contour and filled with coarse material such as straw, wood chips, or manure, to promote rapid infiltration of rainfall runoff into the soil. It has been highly effective on soils with otherwise very poor water infiltration.



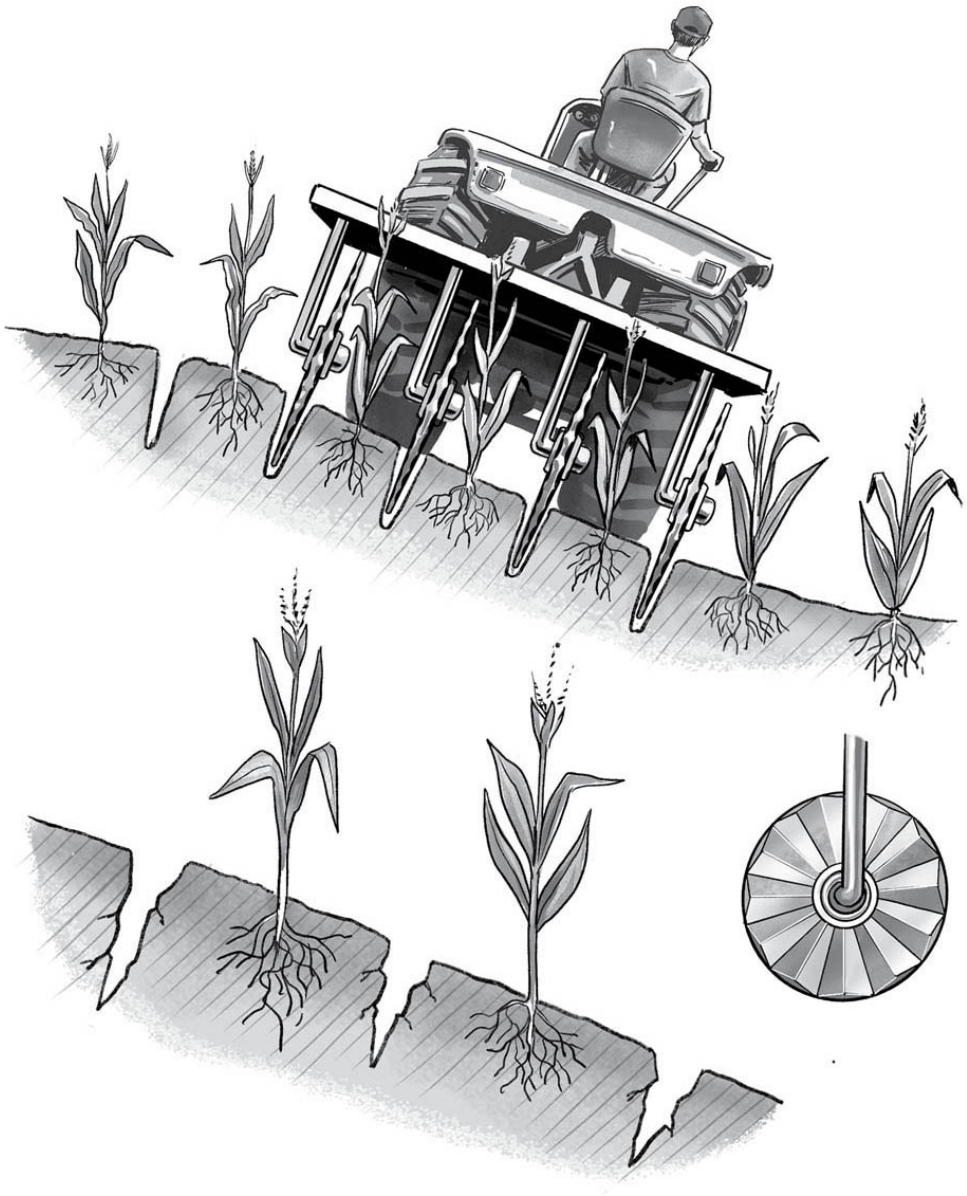
SUBSURFER

A way to mechanize the process of installing vertical mulches has been created at the USDA Dale Bumpers Small Farms Research Center, in the form of a machine called a Subsurfer. The Subsurfer is essentially a combination of a manure spreader and a grain drill. The manure spreader is run backward so that the manure goes to the front of the machine, where it is run through a grinder and dropped into the grain drill attached to the front of the manure spreader. The manure drops into slots created by the grain drill on approximately 10-inch centers, creating a small vertical mulch at 10-inch intervals. If run on the contour, this process nearly eliminates water runoff.

The Coulter Slit

The coulter creates lines of weakness between crop rows. It can also be paired with fertilizer application.

Cracks develop between rows in dry weather, leaving roots intact. If done on contours the cracks may also act as points of entry for rainwater into soil.



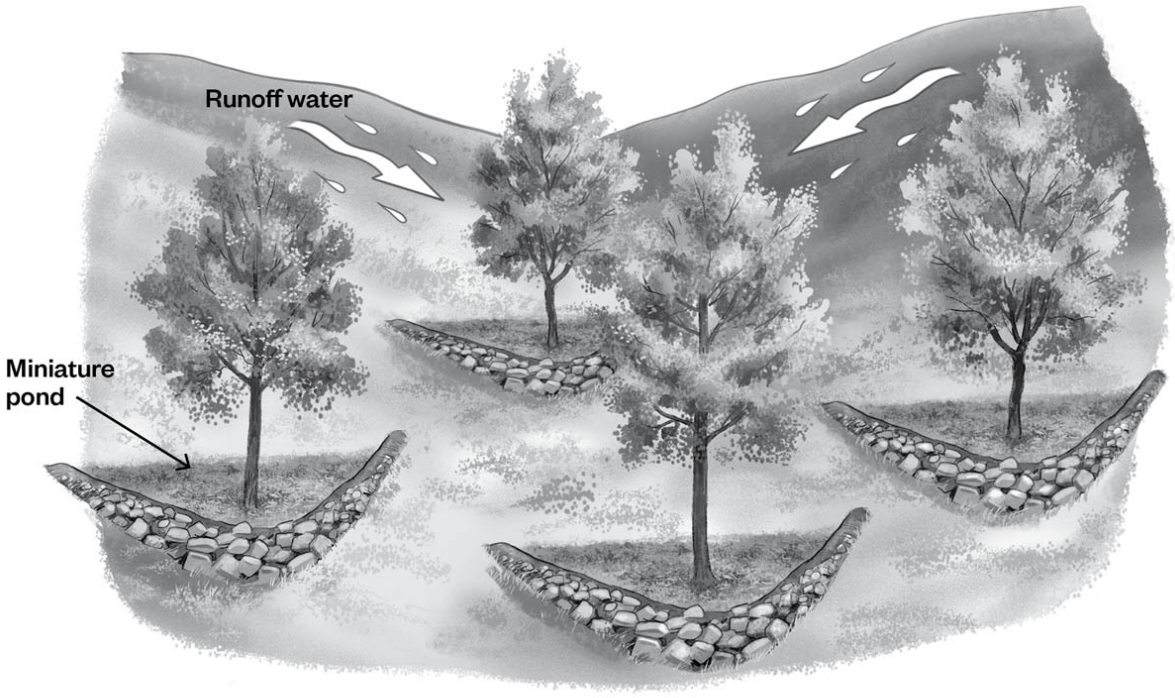
NET AND PAN

Berms can also be laid out in what is called a **net and pan** pattern. A net and pan system is a berm laid out in a sawtooth pattern, with the downhill point of each tooth having a miniature pond to promote holding water long enough for infiltration. Often a tree is planted on the pile of soil resulting from the pond excavation.

Runoff water is funneled to promote growth of a high-water-demand plant.

Net and Pan

A net-and-pan system of berms (also called boomerang berms) is designed to capture rainfall runoff and hold it around individual plants of high value, such as fruit or nut trees.



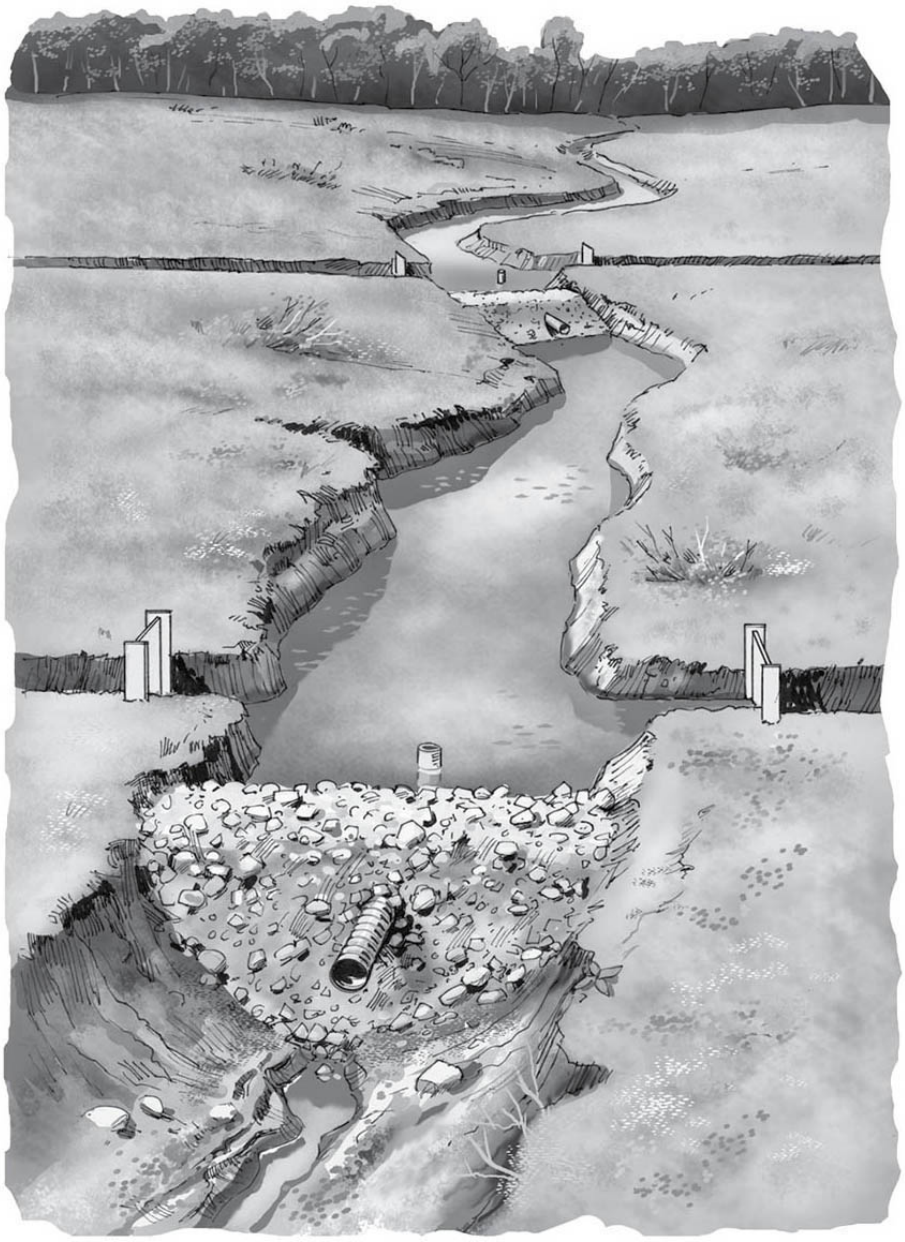
CHECK DAMS

Check dams are small obstructions placed across small streams or watercourses, with a couple of basic purposes in mind. The first is to slow the rate of water flow, so that water has time to soak into the soil, rather than head to the ocean as fast as possible. The second purpose is to trap sediment and keep it from being lost. Additionally, the check dam can be high enough so that during higher water flow, water is diverted out of the channel and onto adjacent land; in this case the structure is called a **water spreader**.

Pit ponds can be dug into land adjacent to and upstream of the check dam to trap and hold runoff water trapped by the check dam that would otherwise be lost downstream. These ponds can be particularly valuable as sources of livestock water, so livestock can be kept out of the stream to improve water quality. There are instances in which seasonal streams that formerly ran only for brief periods after a rain have been converted into streams that have run for several consecutive years after the installation of numerous small check dams. Using check dams is really just an expensive and labor-intensive method to mimic what beavers have historically done for free: slow the movement of water downstream to the ocean and allow it to soak into the soil and replenish aquifers. There are even cases where beavers have been reintroduced to streams in western rangelands. The subsequent hydration of the valley floors from the beaver dams increased the available grazing severalfold over what it was previously.

Check Dams

Also called mini-dams, leaky weirs, and one-rock dams in different parts of the world, check dams are designed to slow water flow in small streams. At this slower pace the moisture spreads out along the sides, soaks into the streambed soil, and replenishes the water table.



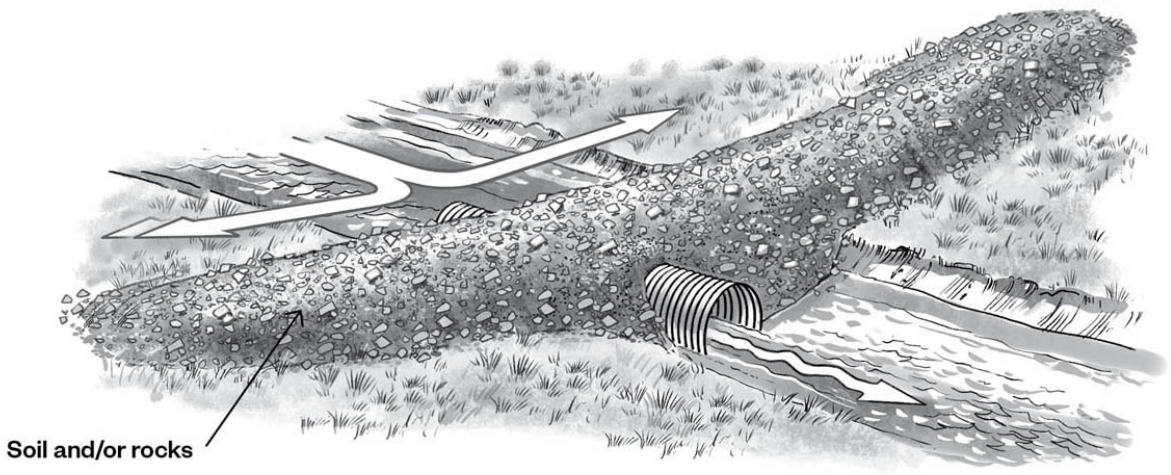
Keyline Irrigation

An Australian visionary named P. A. Yeomans invented the **Keyline irrigation** system. (His son, Ken B. Yeomans, authored a book explaining these principles, called *Water for Every Farm*, which seems particularly useful for pastures; see Resources; see

For Further Reference.) In the Keyline system, landscape features are identified based on their topographical position, as noted in the illustrations.

Water Spreader

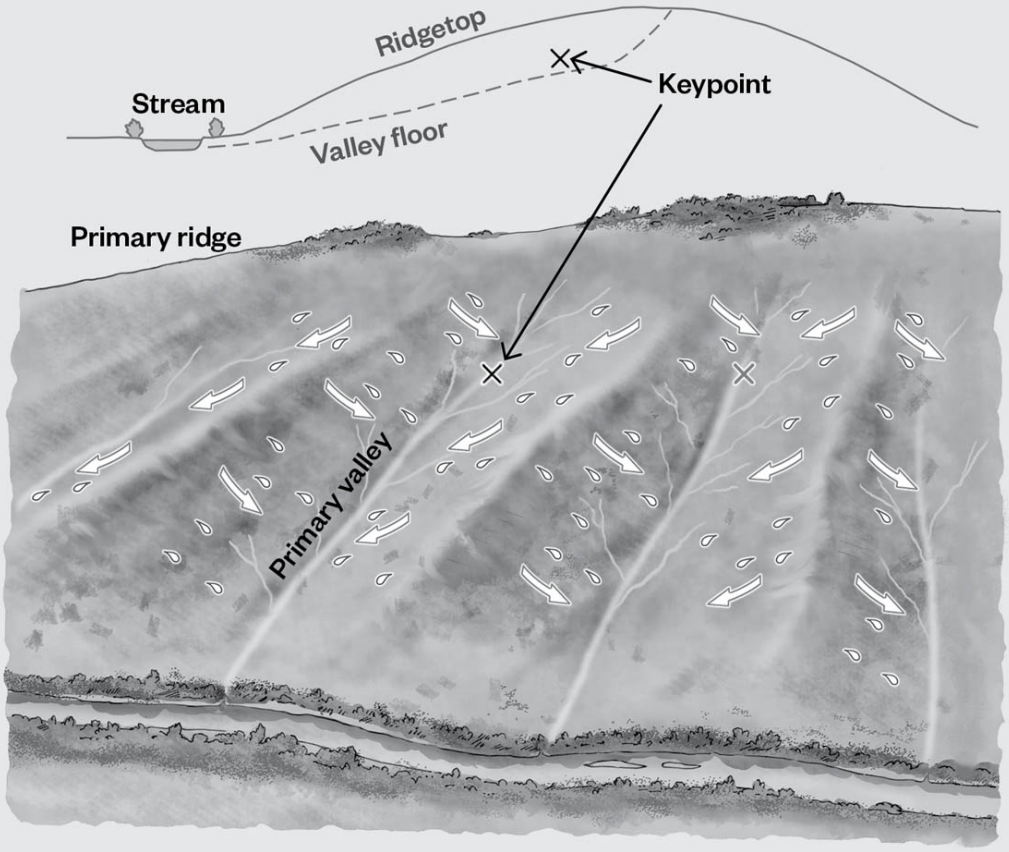
Water spreaders divert water onto uplands during high water flow periods but allow water to move slowly downstream during low water flows.



KEYLINE FEATURES

Drive down any country road and you'll see a landscape laid out as in the illustration at right. There will be slopes with a

ridge at the top and a valley at the bottom. The slope itself will have high points called primary ridges, from which water drains away, and primary valleys, into which water drains. Keyline landforming aspires to hydrate the land more effectively through a series of structural changes to the landscape.

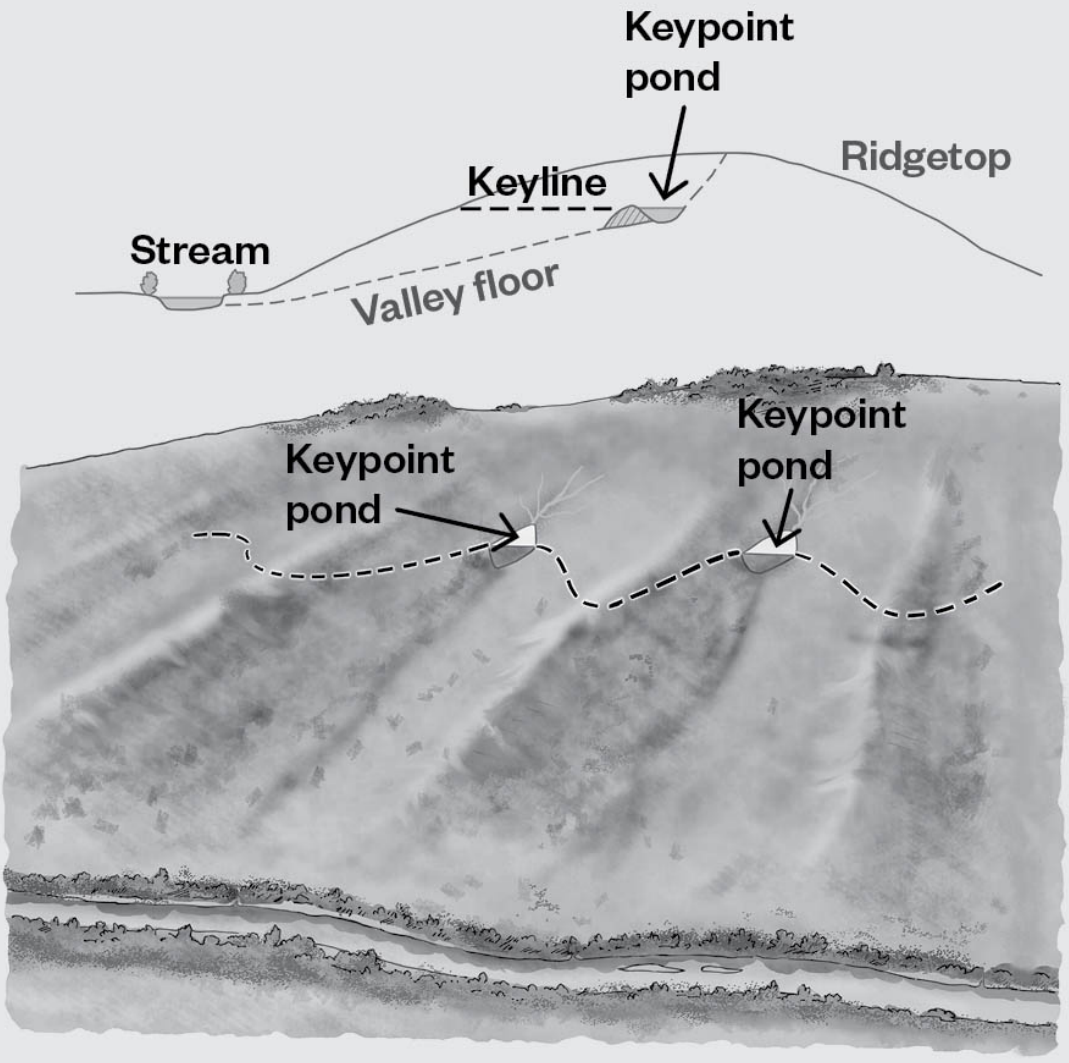


KEYPOINT PONDS

A keypoint is the highest point on the elevation that can feasibly hold water in an impoundment. It is the location in a

primary valley where the slope changes from concave to convex. A keyline is a contour line extending out from this keypoint, with all parts of the line at the same elevation.

In the first phase of keyline landforming, numerous small ponds are constructed at keypoints, noted on the illustration at right, so that gravity can be used to move this stored water anywhere downslope when desired as irrigation water.

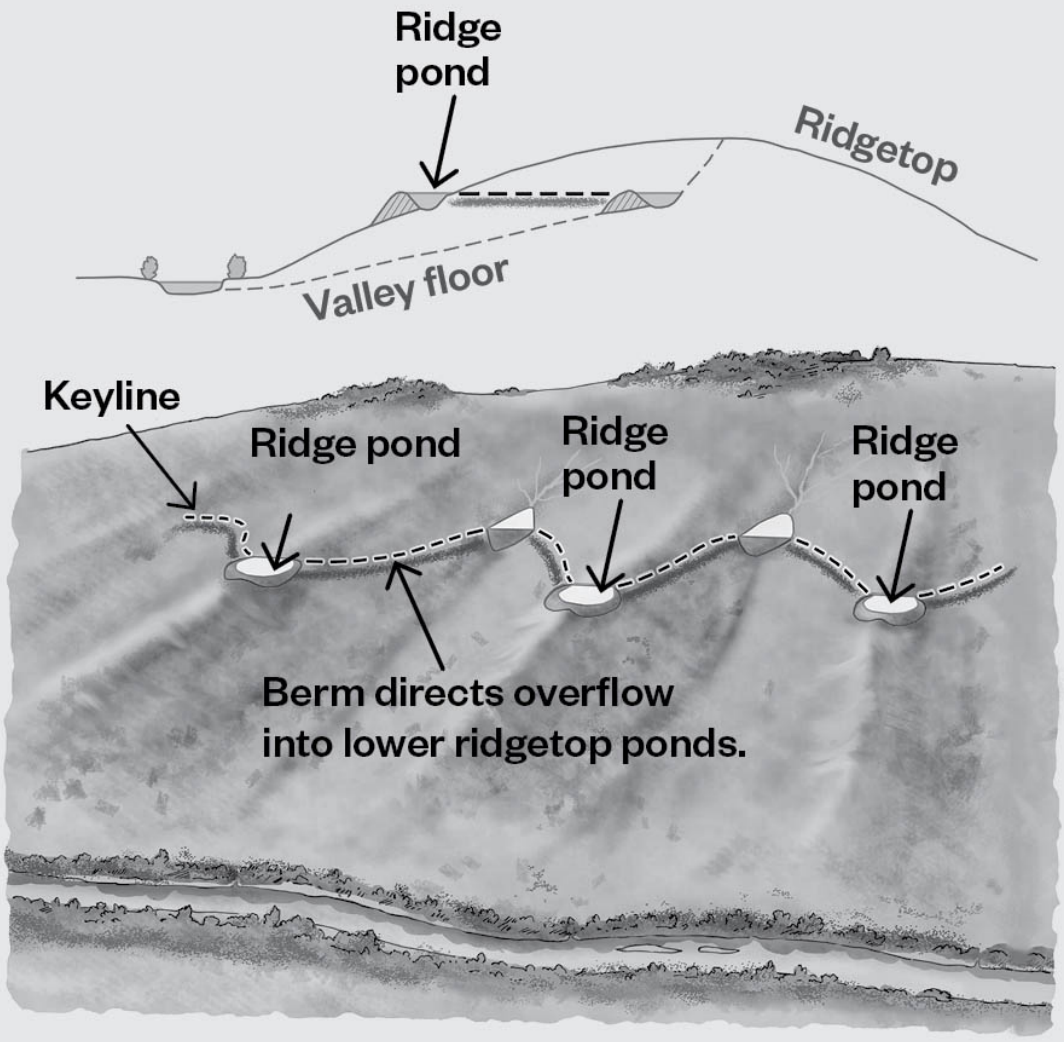


ABOVE: *keypoint ponds*

CONTOUR BERMS

A second component of the Keyline system is a berm built on the Keyline (the contour line connecting all points on the same elevation as the keypoints). This berm will direct any water that overflows from the keypoint ponds toward the ridgetops.

To store this overflow water longer on the ridgetops and allow it time to soak into the normally dry soil on the ridges, you can construct another set of ponds on the ridges. The water in these ridge ponds can be siphoned or pumped over the dam to flow by gravity and irrigate any point below the pond elevation.



ABOVE: *contour berm*

YEOMAN PLOW

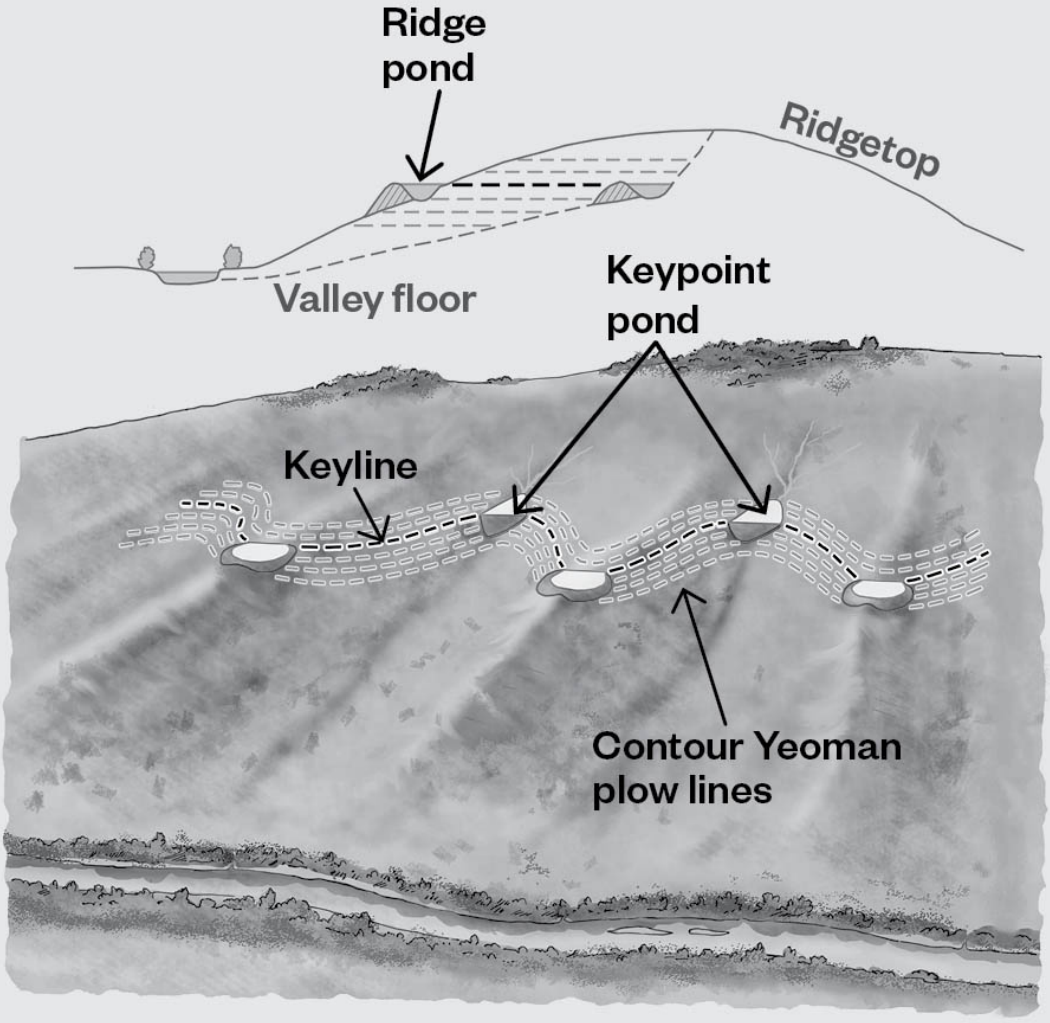
A third component of the Keyline system is the use of a subsoiling chisel, called a Keyline plow or Yeoman plow, to form deep, open channels on the contour to encourage infiltration of water into the soil and reduce runoff. The use of a subsoiler is the most controversial component of this system. Research usually indicates no benefit to subsoiling in

most situations, but proponents of Keyline systems claim it can increase water infiltration and result in rapid creation of new topsoil.

In the past, I have been very hesitant to recommend this component of the Keyline system because I was unable to find research indicating the benefit of the subsoiling, and the research has mostly indicated that there is little benefit, and possibly some detriment, to subsoiling in cropland. You can find my many condemnations of subsoiling throughout this book. However, research indicates that subsoiling can improve water infiltration if the following conditions exist:

- There is no subsequent tillage to fill the channels back in (as so often occurs on subsoiled cropland), so the channels remain open to the soil surface.
- There is a living root system to hold the channels open and keep the channels from collapsing, as would occur on a perennial pasture, particularly with rhizomatous or stoloniferous species of forage plants.
- There is sufficient coverage of the soil surface by residue or living plants to prevent soil erosion from filling the channels with sediment.

Such conditions exist in perennial pastures, where Keyline systems involving the Yeoman plow seem to have the most success. The open channels created by the subsoiler may allow for deeper root growth due to improved oxygen penetration into the soil, and better pasture growth from improved water availability may just add to soil organic matter.



ABOVE: *yeoman plow*

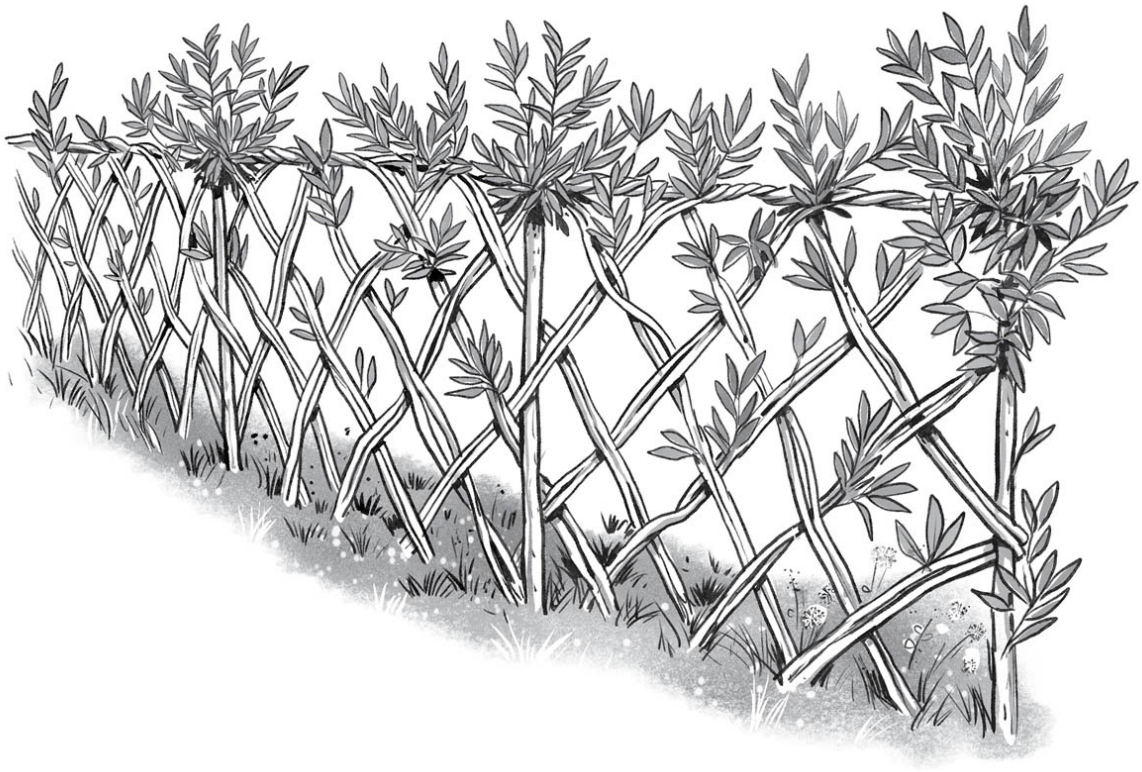
Fredges

A **fredge** is similar to a water spreader—rocks or soil laid perpendicular to the direction of flow of streams and seasonal watercourses to control their flow—except that it is a line of trees.

You create a fredge by cutting poles of willows and cottonwoods (or similar flood-tolerant trees) during their winter dormancy and placing them in a trench or post holes spaced closely in a line and perpendicular to the direction of water flow.

Here are some of the virtues of a fredge:

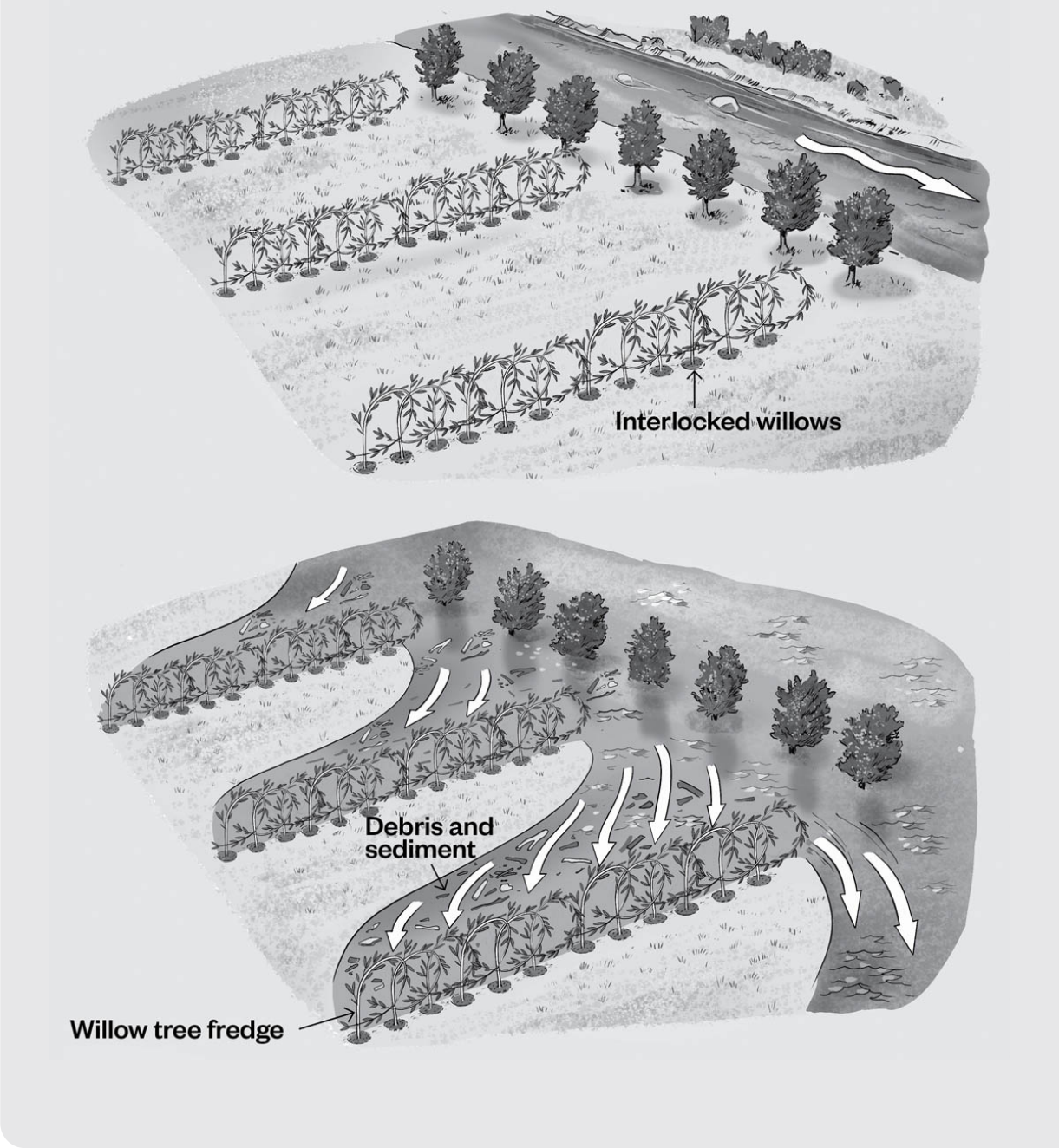
- The poles take root and create a living barrier that grows stronger every year, rather than needing more repair and maintenance as time goes on.
- During high water flow, the trees trap brush and debris, creating a natural check dam/water spreader.
- The trapped woody debris and sediment create a very fertile growing site for riparian vegetation that can provide valuable forage during drought periods.
- The willows and cottonwoods can also be trimmed and used as emergency forage.
- The tree lines can also serve as livestock fences that are quite resilient to flood damage, especially if they are interlocked to form a **pleached** fence (see illustration below).



ABOVE: *Fredges are tree rows whose branches are interwoven, or pleached. Placed along rivers, perpendicular to the direction of water flow, they can also function as flood-tolerant fences.*

HOW FREDGES WORK

During floods, fredges trap debris high in organic matter and fertility. After each flood, tree roots grow into the trapped debris, making the fredge stronger with each flood event.



Counterproductive Landforms

Not all landforming measures are positive, and many that are routinely built can be quite destructive. One such practice is the channelization of streams and rivers, which is the replacement of a meandering stream with a straight channel. The intent is to

minimize the area taken up by the river channel to facilitate farming or development next to the river. Thousands of miles of streams have been channelized for this purpose.

What channelization does, however, is to change a stream with a slow, tortuous, and relatively gently sloped pathway into a stream with a straight and steep pathway. This has the effect of moving water much more rapidly downstream. Channelization often has little negative effect on the adjacent properties but greatly increases the amount of flooding downstream.

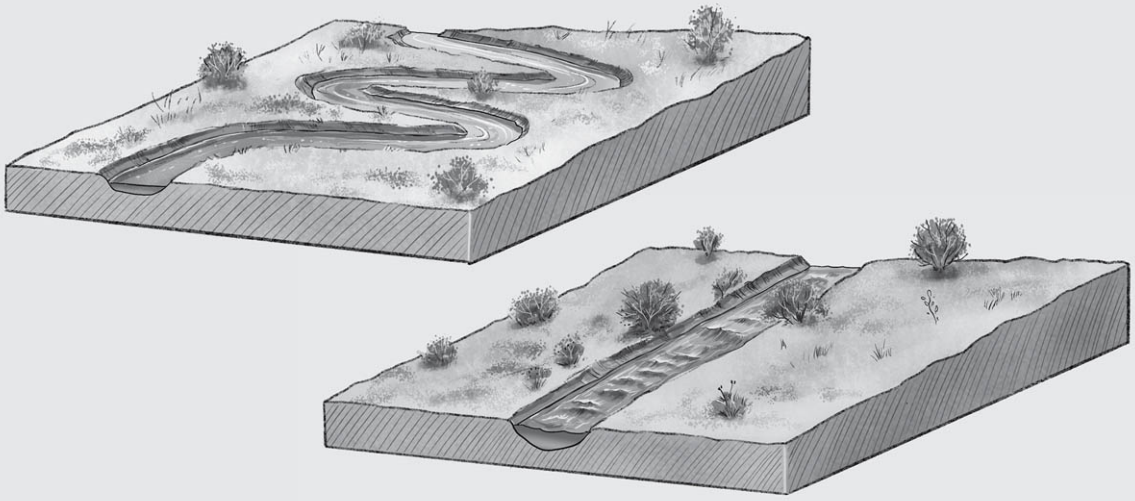
Levees are another example of passing a problem to your neighbor below. Levees are designed to fight gravity and keep flood water contained in the stream rather than moving out onto the floodplains, as it would otherwise do naturally. Water on the floodplains moves downstream slowly. Water retained in the river by levees moves rapidly downstream to increase the severity of flooding there.

Again, the intent is to protect cities and farms from flooding, a noble goal. But there are two major issues with levees. One is, obviously, that levees pass the flood water to the downstream neighbors and add to their problems.

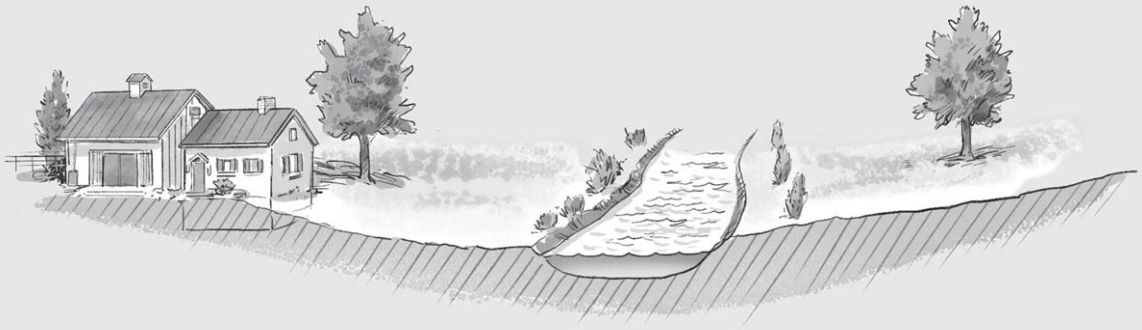
Secondly, gravity is perhaps the strongest, most reliable force in nature. Building on floodplains adjacent to a large body of water sitting at a higher elevation than you—with just a levee in between—is not very smart. This fact was driven home by the failing of the levee system around New Orleans during Hurricane Katrina in 2005. Given enough time, gravity always wins.

Meandering Stream, or Channel?

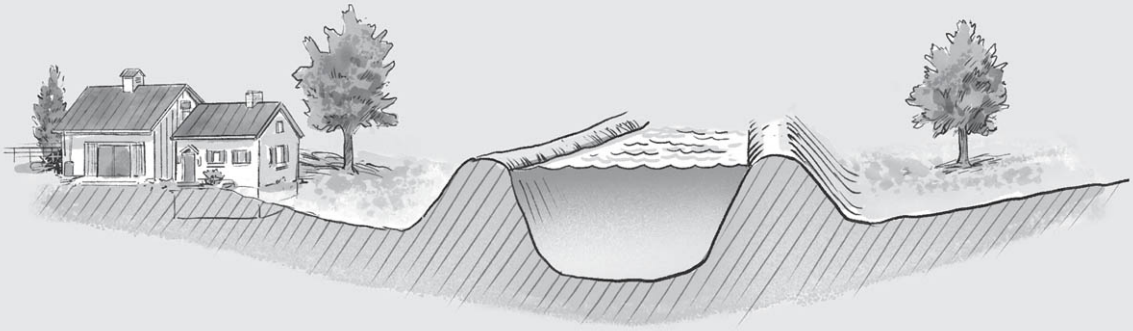
In a naturally meandering stream, water moves slowly downstream, with low risk of erosion or downstream flooding. In a channelized stream, water moves rapidly downstream, with a high risk of erosion and downstream flooding.



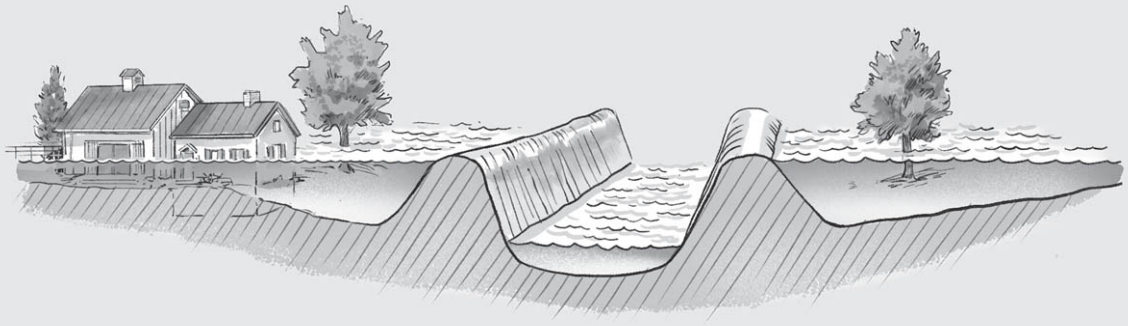
The Problems with Levees



ABOVE: *A river without levees*



ABOVE: *A river with levees during high water. The water level is at a higher elevation than the floodplain and risks levee failure and increased downstream flooding.*



ABOVE: *A river with levees postflood. The levees retain the flood waters and prolong their presence.*

Dealing with Saline and Sodic Soils

Some of the most difficult soils to farm are soils that have been affected by salts (called **saline soils**) or by sodium (**sodic soils**). Soils that have high levels of both sodium and salt are referred to as **saline-sodic**.

Many formerly productive farmlands throughout the world have been abandoned because of salinization or sodium buildup, including lands in the Middle East and in California. The main cause of soils becoming more saline or sodic over time is irrigation with water containing salts or sodium.

Salt and Soil

Salt primarily affects soil by its **osmotic potential**, or attraction for water. Salt can exert a greater "pull" on water than plants can; thus, the primary effect of saline soils is an inability of plants to access water.

We usually think of salt as being sodium chloride, and while that may be the most common salt in soil, many others, such as calcium chloride, sodium bicarbonate, magnesium chloride, magnesium sulfate, and sodium sulfate can be present in soil.

The higher the water solubility of the salt, the stronger its attraction for water. The saltiness of a soil is usually measured by

its electrical conductivity (EC), measured in millimhos per centimeter (mmhos/cm). A soil with an EC greater than 4 is said to be saline. An electrical conductivity of 25 or greater may completely prevent plant growth.

Sodium and Soil

Sodic soils have high levels of sodium attached to the clay particles. Sodium causes the clay to break into individual particles, the opposite effect of aggregation. Since aggregation facilitates the movement of air and water into a soil, a sodic soil has very poor movement of air and water into the soil.

HOW SALINITY AFFECTS PLANTS

CONDUCTIVITY (MMHOS/CM)	EFFECT ON PLANTS
< 2	Negligible
2–4	Sensitive plants impacted
4–8	Most plants impacted
8–16	Only tolerant plants not impacted
16+	Only tolerant plants survive

CLASSIFYING SALT-AFFECTED SOIL

SOURCE: R. L. Donahue, R. H. Follett, and R. W. Tulloch, *Our Soils and their Management* (Interstate Publishing, 1976).

CLASSIFYING SALT-AFFECTED SOIL

CONDUCTIVITY (MMHOS/CM)	SOIL PH	EXCHANGEABLE SODIUM (%)	CLASSIFICATION
> 4.0	< 8.5	< 15%	Saline
< 4.0	> 8.5	>15%	Sodic
> 4.0	> 8.5	>15%	Saline-sodic

SOURCE: R. L. Donahue, R. H. Follett, and R. W. Tulloch, *Our Soils and their Management* (Interstate Publishing, 1976).

Remediating Saline and Sodic Soils

Restoring saline and sodic soils can be expensive and can take many years. Before you begin such a project, ask yourself whether the payoff will be worth the expense. It is foolish economically to undertake a $2,000-per-acre remediation project if the land will be worth only $1,000 per acre when it is finished—unless you anticipate future land price increases or if the increased productivity of the land exceeds the economic cost, such as when food production is paramount. In Israel, food independence and security are so critical that many farmers undertake remediation projects without regard to cost because they need every bit of land to produce food.

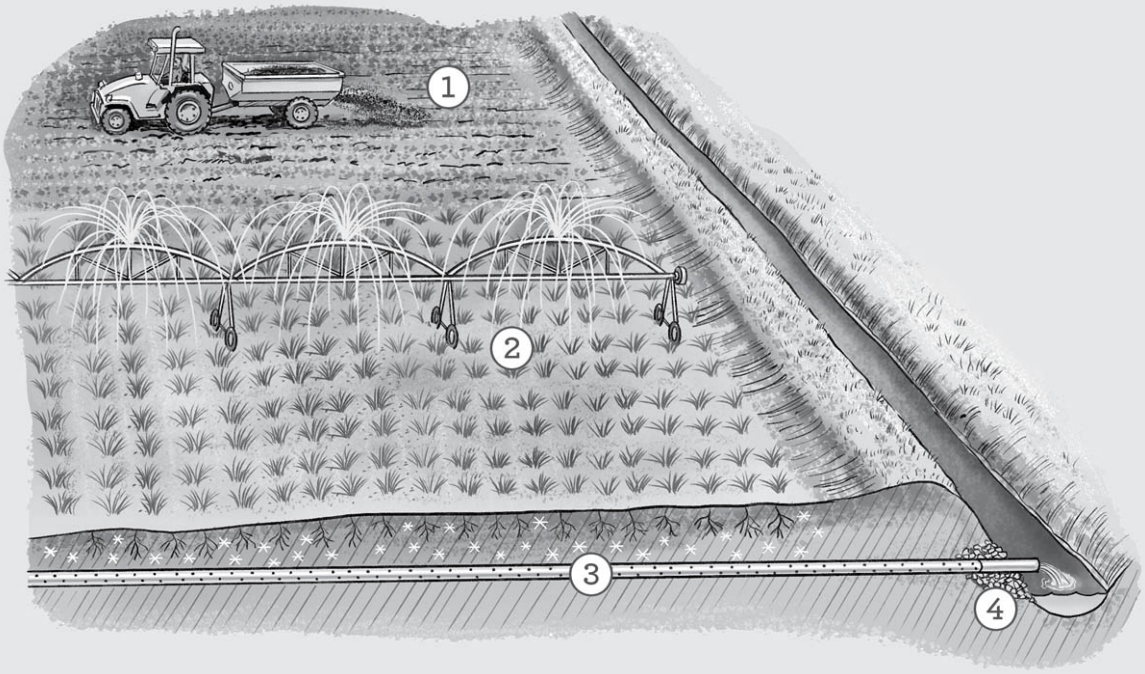
Here are some practices to consider:

Install proper drainage. The salt and sodium need to have a means of escaping the soil. Underground drainage tubing is

usually the best means to accomplish this, but the tubing needs an outlet at a lower elevation than the field. This may or may not exist naturally; it may be necessary to move the salty water underground a long distance from the drainage before a lower elevation area is reached for disposal. It is also important to recognize that the area into which this salt- or sodium-laden water is disposed will increase in saltiness.

Add calcium. The second step in a sodic or saline-sodic soil is to apply a high-calcium salt, such as gypsum, to displace the sodium from the clay particles. Calcium will **flocculate** the soil (another term for increasing aggregation), which will improve water and air movement. If the soil is saline but low in sodium, application of gypsum may not be necessary.

Redeeming Saline and Sodic Soils



ABOVE: *Four steps in bringing saline and sodic soils back to productivity:*

1. Spreading gypsum
2. Surface or sprinkler irrigation
3. Subsurface drainage
4. Escape route for high-sodium water

Note: This remediation step requires approximately 2 tons of gypsum per acre for every reduction of 1 mEq/L of Na (a

measurement appearing on a soil test for salinity issues) to be displaced on the cation exchange capacity.

Flush the salt or sodium out of the profile. In arid areas, where most salt problems occur, you may need to irrigate. In more rainfed areas, this may be accomplished with natural rainfall. The source of water to flush the land ideally is very low in salt and sodium, but sometimes the only water available contains some level of those elements.

Keep a mulch on the soil surface. Mulch retards evaporation of water, which helps maintain plant growth and slows the movement of salt to the soil surface. It also improves the effectiveness of any leaching operations. These lands should be farmed without tillage to maintain a surface mulch and should be cover-cropped with high-residue salt-tolerant plants, such as barley, to create a mulch if none exists.

Plant crops that tolerate the soil conditions. You can do this on any area affected by salinity or sodium. On arid areas, however, where drainage and irrigation are not feasible or are too expensive, and where gypsum may be too costly for the productive potential of the land to ever pay it back, this may be the only feasible and economical choice.

The chart on the facing page lists some of the more salt-tolerant crops. Note that:

- in general, perennial plants tolerate salinity better than annuals do, since the seedling stage is most sensitive to salinity problems (although this is not an absolute rule);
- some of the most salt-tolerant plants have value as forages, such as forage kochia, four-wing saltbush, Old Man saltbush, tall

wheatgrass, alkali sacaton, green wheatgrass, bermudagrass, and willow trees;

- among cereal grains, barley has the most salt tolerance. Cotton and sugar beets are known for good salt tolerance.

Inoculate crops with mycorrhizal fungi. This can be a highly effective means of improving the tolerance of almost all plants. The **hyphae** (fine threadlike fungal bodies extending throughout the soil) help the plants access more water, reducing the impact of the osmotic potential of salt. In addition, the glomalin produced by the hyphae help aggregate the soil and facilitate better movement of air and water in the soil, which eases flushing of the salt and improves root growth for better water access over time.

Mycorrhizal fungi can take salt into the hyphae, then move it into little branches of hyphae and wall it off so the salt is taken out of the soil solution until the hyphal walls break down years later.

HOW MYCORRHIZAL INOCULATION AFFECTS TOMATO YIELD IN SALINE CONDITIONS

SOIL	TOMATO YIELD KG/SQUARE METER		INCREASE FROM INOCULATION
	NONINOCULATED	INOCULATED	

SOURCE: G. N. Al-Karaki, "Nursery inoculation of tomato with arbuscular mycorrhizal fungi and subsequent performance under irrigation with saline water," *Scientia Horticulturae* Vol 109, Issue 1 (2006): 1–7.

HOW MYCORRHIZAL INOCULATION AFFECTS TOMATO YIELD IN SALINE CONDITIONS

Nonsaline	5.8	7.5	29%
Saline	3.3	5.3	60%

SOURCE: G. N. Al-Karaki, "Nursery inoculation of tomato with arbuscular mycorrhizal fungi and subsequent performance under irrigation with saline water," *Scientia Horticulturae* Vol 109, Issue 1 (2006): 1–7.

Salt Tolerance of Different Crops

Within their groups these plants are listed in order of use (field crop; forage crop; market vegetable; market fruit), and within those uses, their families. The most common way to measure salinity is by electrical conductivity, and the unit of measurement is millimhos per centimeter (mmhos/cm).

LOW TOLERANCE (0–4 mmhos/cm)

- Field beans
- Soybeans
- Field peas
- Alsike clover
- Red clover
- White clover
- Redtop
- Apple
- Pear
- Orange
- Grapefruit
- Almond
- Apricot
- Plum

Timothy	Strawberry
Celery	Lemon
Cucumber	Avocado
Radish	

MODERATE (4–8 mmhos/cm)

Corn (maize)	Broccoli
Flax	Lettuce
Rye	Potato
Sorghum	Pepper
Wheat	Tomato
Rice	Cantaloupe
Alfalfa	Fig
Orchardgrass	Grape
Smooth brome	Olive
Reed canarygrass	Pomegranate
Pubescent wheatgrass	

HIGH (8–16 mmhos/cm)

Barley	Garrison creeping foxtail
Rapeseed	Table beet
Sugar beet	Spinach
Tall fescue	Asparagus
Russian wildrye	Date palm
Slender wheatgrass	Four-wing saltbush
Bird’s-foot trefoil	

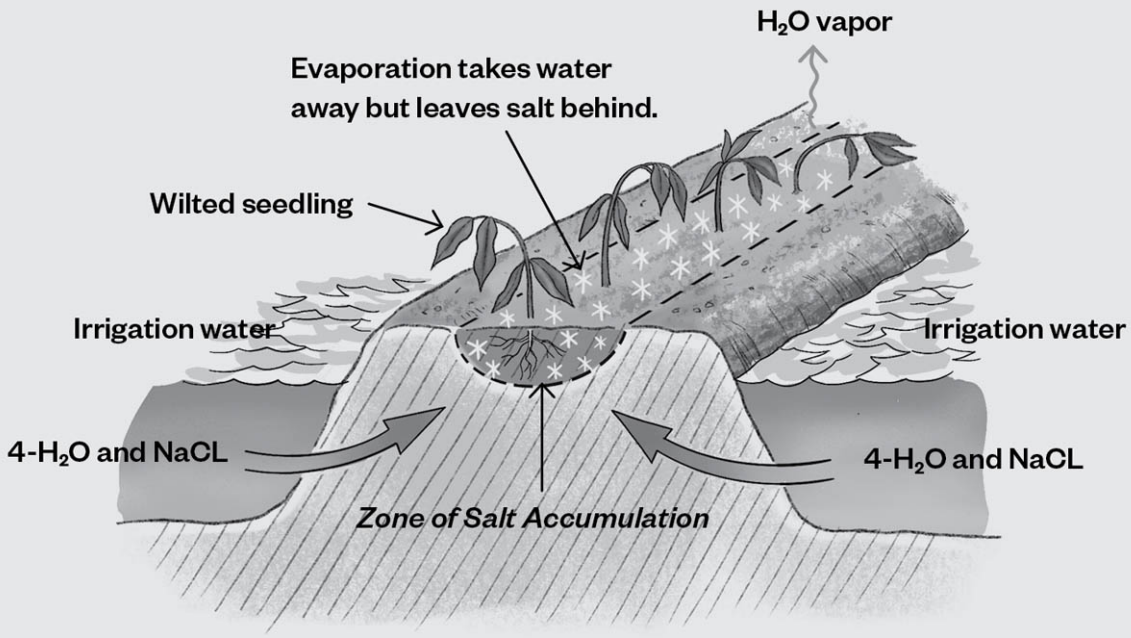
Sweet clover	Forage kochia (prostrate bassia)
Strawberry clover	Old man saltbush
HIGHEST (16–20 mmhos/cm)	
Bermudagrass	Tall wheatgrass
Green wheatgrass	Alkali sacaton
NewHy wheatgrass	

Add biochar. Researchers in China have found this substance to dramatically improve plant growth on salty soils. Biochar can be quite expensive on a field scale application, but small amounts placed in furrow with seed to enhance plant establishment can be fairly economical and successful. (See further discussion in Chapter 6.)

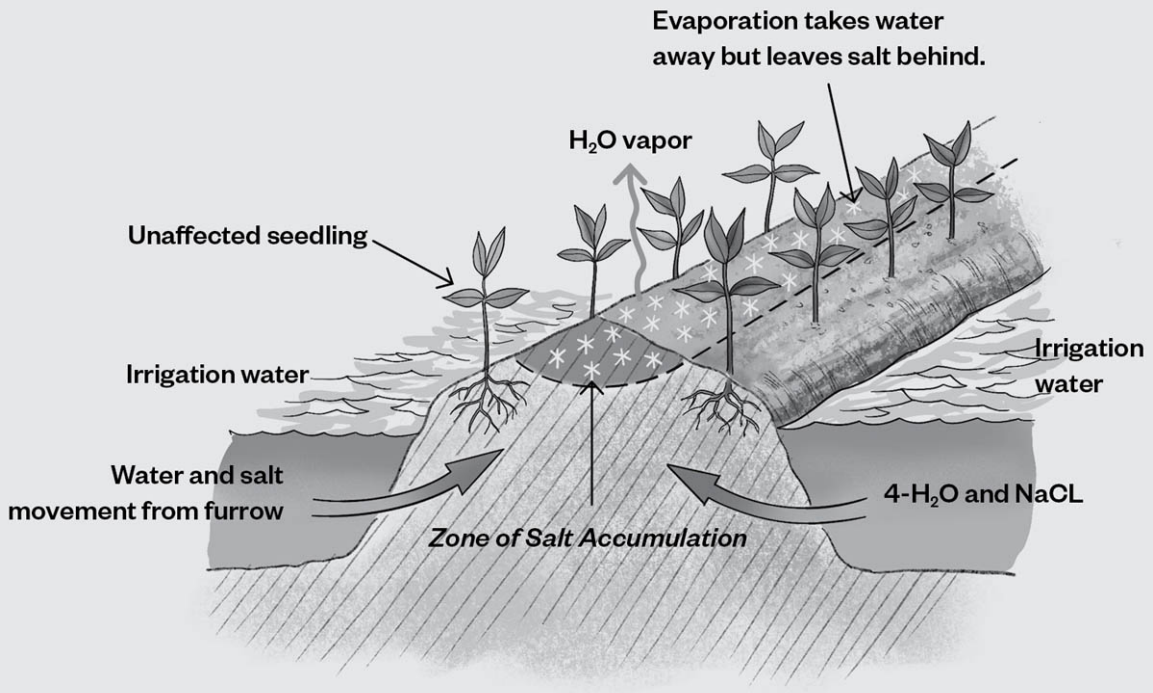
Build ridges to protect crops from salt. Plant crops in twin rows on the "shoulders" of peaked ridges to keep the salts from affecting germination. The diagram below shows how the salt moves with moisture, accumulating in the ridgetops and below the furrows, and the crops can be placed where the salt will least affect them.

Managing Salt in Furrow-Irrigated Fields

Twin rows on the shoulders of peaked beds are less affected by salt than is a single row down the center of a peaked bed.



ABOVE: *single rows*



ABOVE: *twin rows shoulders*

Preventing the Next Dust Bowl

JOHN NISWONGER, Wallace, Kansas

One of the toughest places to farm in North America is the far western High Plains, a region of low rainfall (12–16 inches [300–400 mm] annually), high summer temperatures, and strong moisture-sapping winds. Land that's any worse than this they don't even try to farm: It is left for livestock.

Farming here has always been marginal, particularly in the early years of settlement, when pioneers from the Eastern US or immigrants from Europe tried to farm the way they did back home, with predictably disastrous results.

The first technique used to stabilize crop yields was that of fallow, a period in which the land grew nothing and was tilled to prevent weed growth from using moisture. The idea was that you could store the moisture from one year, add it to the next year's rainfall during the crop, and get a good crop in the second year. Initially this was somewhat successful, but every year the tillage lowered the soil organic matter level and destroyed its structure. When the rains stopped during the 1930s these tilled fields began to simply blow away and no longer stored moisture when it fell, and the region turned into the Dust Bowl. (See Figure 3.5.)

Soon after, Charles Sherwood Noble from Alberta, Canada, visited the region, went home, and created a tool still used today. Called the Noble blade, undercutter, or V-blade, it killed

weeds by cutting them below the soil surface rather than flipping the soil over and baring it to sun and rain the way a moldboard or disk plow does. The tool left the crop stubble on top of the ground rather than burying it, which not only retained more moisture in the soil but also stopped the wind from blowing the soil away.

Chemicals and Consequences

A few decades later, the development of herbicides like paraquat and glyphosate let farmers skip tillage altogether and leave the residue completely untouched. This led to no-till farming, which allowed the fallow period to store twice as much moisture as tilled fallow, greatly stabilizing crop yields.

In recent years, however, the development of herbicide-resistant weeds, such as Palmer amaranth and kochia (the “tumbleweed” seen in Western movies), has forced farmers to apply multiple herbicides to control weeds without tillage. This put these farmers in an undesirable dilemma: either apply multiple, expensive combinations of herbicides to control weeds in fallow, or go back to tillage down the same path of soil destruction and poor moisture retention that once led to the Dust Bowl.

Best Solution: Bring in the Herd

One farmer in this area, however, is changing the way he does things altogether, with a system that is more moisture efficient and profitable than traditional grain cropping. John Niswonger of Wallace, Kansas, has replaced most of his grain

crops with annual pasture crops, grazed during periods when his native grass pastures of mostly low-growing buffalograss and blue grama are either not productive or in dire need of a rest period.

The native grass is also now grazed in a mob-grazing system, each paddock being grazed once in the early part of the summer, rested the remainder of the growing season, and not grazed again until a frost has sent the grass into dormancy, a period in which grazing does not harm it. The grasses are more tolerant of grazing in the early summer than in late summer, and this system allows them to fully charge their roots with carbohydrate reserves and build a moisture-conserving mulch during late summer.

Part of the cropland is planted to a diverse blend of summer annual forages (like sorghum-sudan, cowpeas, sunn hemp, pearl millet, mung beans, and sunflowers) for grazing during the late summer while the native pastures rest. After frost, the native pastures can be grazed off without harm to the root growth to provide fall grazing.

Other cropland acreage is planted to a mixture composed of a forage sorghum that is sterile (doesn't produce grain) and plants that hold high-protein seeds in their pods for winter grazing. The mixture retains adequate grazing quality for a nonlactating cow even in the dead of winter and, since it sticks up above the snow, produces a high level of biomass that can be grazed even during a blizzard. Still other cropland can be planted to a mixture of winter annual forages like rye and winter peas to provide early spring grazing before native grass pastures green up in summer.

Together with the native grass being grazed in early summer and in fall, cattle can be grazed twelve months of the

year most years, with little need of feeding hay. Eliminating that need then eliminates expensive haymaking equipment: What little hay is needed for emergency purposes can be purchased and kept in storage. The grazing cycles fertility back onto the cropland, and the legumes in the grazing mixtures make nitrogen. Consequently there is very little need of purchased fertilizer, since no fertility leaves the farm in the form of grain.

Bottom Line

Eliminating grain harvesting also removes one of the biggest capital expenses on the farm: the grain combine. A new one complete with a corn picker and platform header attachment for wheat might cost over $750,000 dollars. The value of the cattle produced per acre exceeds the value of the grain formerly produced on the same acre. Perhaps most importantly for the area, grazing crops use less moisture than the grain crops did, making wasteful and soil-destructive fallow less necessary. Most of the moisture used by a grain crop is used during the grain fill period, so grazed crops that do not produce grain use much less total moisture than grain crops.

Perhaps most importantly now, the herbicide-resistant weeds that are so expensive to control in a traditional grain-cropping system are actually very nutritious and palatable grazing plants; rather than being weeds as they are in grain cropping, they are valuable additions to grazing mixes, and the seed is free! Simply grazing the weeds instead of pouring out complex chemical concoctions saves an incredible amount of money.

But other benefits are beginning to show as well. The native grass pastures have shown a remarkable increase in vigor, despite carrying several times more grazing days per acre as formerly, due to long rest during vulnerable periods that allow considerable regrowth to act as a mulch. This mulch has held much more soil moisture than nearby pastures grazed in the traditional season-long continuous-grazing system, and streams that used to run only briefly after a rain now run most of the year. What effect will this added soil moisture have on the underlying Ogallala Aquifer, which has been declining for decades?

All of these factors contribute to a vastly improved bottom line, and John reports that he is making much more money in this system than he was making while growing grain crops.

ADD IT UP

To put it into perspective, a typical native grass pasture in this area requires 12 acres to carry a cow for 150 days, or roughly 12.5 grazing days per acre. A typical crop rotation would be wheat–sorghum–fallow, which produces a crop of roughly 30 bushels of wheat per acre, on average, and 70 bushels of sorghum per acre, on average in a three-year period, with a roughly ten-month fallow between crops.

A farmer in a traditional system with 1,200 acres of pasture and 1,200 acres of cropland could produce about 100 calves worth around $900 at current prices for $90,000 gross cattle returns. He would need four months of hay feeding to do so, with the rest of the time spent grazing sorghum stalks after harvest. He could produce about 12,000 bushels of wheat (400 acres × 30 bushels per acre at $4 a

bushel, worth about $48,000) and about 28,000 bushels of sorghum grain (400 acres × 70 bushels at $3 a bushel, worth about $84,000). That is a total farm gross income of $222,000.

Out of this gross income, the farmer has to pay rent or make land payments; make payments on a tractor, planting equipment, a combine, trucks to haul grain away, fuel to power all that equipment, fertilizer to replace the fertility shipped away in the grain, and hay or haymaking equipment; and either practice tillage to control weeds or employ a witches' brew of chemicals to control the now herbicide-resistant weeds.

By contrast, a farmer with the same land base could raise 300 calves for a gross total of $270,000 on an all-pasture system based on what John is doing and can eliminate almost ALL the expenses described in the grain farming system, other than land cost, tractor, and planting equipment. John has shown us an example of a system that can make farmers profitable again in a region in which farming is very marginal; perhaps if more farmers copied John's approach, the entire region could once again become prosperous.

LEARNING BY DOING

My Own Remediation Success

When I bought my second farm, it had several small areas with bad saline-sodic issues, with EC (electrical conductivity) readings as high as 27 in some spots. The first year I farmed this field I planted sorghum on it, a crop with decent

salt/saline tolerance. Still, I had big dead circles in my sorghum, with a ring of weedy annual kochia (a very salt-tolerant plant) surrounding the dead circles.

I resolved to address these areas. Irrigation water is not available at this farm, so my options were limited. The first thing I did after sorghum harvest was to plant a cover crop of barley. I also inoculated the barley seed with mycorrhizal fungi. This cover crop grew very successfully, and I sprayed it down to leave it as a mulch.

I then planted soybeans, with a variety containing what is called a chloride excluder trait for improved salinity tolerance. Soybeans ordinarily do not have good salinity tolerance and are a poor choice for these areas, but most of the field was not saline-sodic, so I thought it worth a try. Besides, the soybeans would be a good test for my salinity remediation efforts.

The soybeans actually *grew* quite well, even in the spots with the high EC readings where nothing, not even salt-tolerant kochia, grew the year before. The beans did not *yield* well in those areas, but at least the areas were green instead of brown. Each and every year, these spots have gotten better. I have since planted these areas to salt-tolerant perennial forages such as green wheatgrass, which has really taken off after an initial slow start.

The remediation project has been successful as well as economical. I skipped the drainage installation, the irrigation, and the gypsum application; if conditions and cash flow allow, however, the drainage and gypsum are still options. I have

spread small amounts of ashes and charcoal from my woodburning furnace in the worst areas, sort of an improvised biochar and calcium combination. I have not really seen any major benefits from that, but it could just need some more time.

CHAPTER 4 SUMMARY

- Most farmers consider a lack of soil moisture as their most limiting factor to crop production.
- We feel powerless to control the amount of rainfall we receive, but there is accumulating evidence that we can control the weather, because we have been affecting the weather, just not in the way we would prefer. Our management of the land has most likely been causing our rainfall to be less frequent but more severe when it does occur.
- The amount of rainfall we receive is not as important as the amount of rainfall made available to our plants; in all too many cases, the amount of effective rainfall as a percentage of total rainfall is shockingly low. We create our own droughts through poor soil management, which causes excessive runoff and evaporation, low soil water-holding capacity, and shallow root systems for our crops.
- There are means to improve the infiltration of rainfall, such as the creation and retention of surface soil mulches by eliminating tillage and incorporation of cover crops into the crop rotation.
- You can remove salts from soils through subsurface drainage, along with maintaining a surface mulch and perhaps applying calcium compounds and charcoal. An increase of 1 percentage

point of soil organic matter can increase the ability of a soil to hold up to 25,000 more gallons of water per acre.

- Landforming methods such as terraces and swales can be used to retain more water on the landscape by slowing or preventing water from running off after it exceeds the infiltration capacity of the land.
- Soils with excess salt pose particular issues with water management, as salt draws moisture away from plant roots. Salt can be removed from soils through subsurface drainage, combined with maintenance of a surface mulch and perhaps applications of calcium compounds and charcoal. Mycorrhizal fungi can improve tolerance of plants to high salt levels. If the cost of these remedies exceeds the productive potential of the land, planting the land to salt-tolerant vegetation may be more economical.

05

Soil Biology

For almost all of the period we call “industrial agriculture,” we have farmed under the assumption that soil was a relatively inert material, just a vessel holding water and fertilizer, which were drawn up by plant roots for their use, and that all the microbes in the soil were bad for our plants and needed to be eliminated. For too long, too many of us in agriculture were grossly ignorant of the fact that virtually every desirable process that takes place in the soil is mediated by soil microbes. This includes all the biological processes that turn sterile rock particles (sand, silt, and clay) into productive soil.

As someone wise once stated, the Moon and the Earth have identical geology; the difference between them is biology. How much better a Planet Earth could we have if we learned to harness soil biology rather than trying to subdue it?

Earthworms

When thinking of soil animals, the first organisms a lot of people think of are earthworms, and for good reason. Earthworms are present in great numbers in very productive soils and are conspicuously absent in poor soils. This raises a common question: Do earthworms create productive soils, or simply thrive in them? The answer seems to be *both*.

The Diet of Worms

Earthworms are unique among soil animals in that they ingest large quantities of soil itself, rather than just organic materials. Like most soils, the ingested soil is a mixture of sand, silt, and clay. You could describe sand and silt as little bitty rocks, while clay is the result of rock decay.

Earthworms have no teeth; instead, they have gizzards just like birds do. Birds swallow rocks in order to grind food inside their gizzards, while earthworms ingest tiny rocks in the form of sand and silt that serve the same purpose.

Inside the gizzard, sand and silt grind against each other, breaking organic materials into smaller bits. This blend of rock particles and organic materials supports a set of organisms called **lithotrophs** that live off rock particles.

CASTS

The earthworms digest these organisms along with the organic matter and deposit the result of this digestive process in feces called **casts**. The casts contain less sand, and more silt and clay, than does the ingested soil, a result of the grinding and microbial decay of the rock particles.

Interestingly, earthworm casts have far more available mineral fertility than the ingested soil does (this is important evidence in favor of the "earthworms increase soil productivity" theory). The casts also maintain much greater aggregate stability than the ingested soil, creating a highly favorable soil structure that is conducive to plant growth. (See Figure 5.4.)

Tunnels

Earthworm tunnels, particularly those of deep-burrowing species such as nightcrawlers (*Lumbricus terrestris*), act as large, continuous macropores to conduct both water and oxygen into the soil. Earthworm tunnels are stabilized by the slime earthworms secrete from their skin, a substance that serves as a very rich food source for microorganisms, making the lining of these burrows highly biologically active.

Earthworms Down Under

Some of the best work in documenting the benefits of earthworms to soils comes from Australia and New Zealand, where earthworms are not native; therefore, “control areas” are easy to achieve compared to areas in which earthworms have been inoculated.

From the pamphlet “Benefits of Earthworms” by the Department of Primary Industries, New South Wales, Australia: “Research into earthworms in New Zealand and Tasmania found earthworms introduced to worm-free perennial pastures produced an initial increase of 70–80 percent in pasture growth, with a long-term 25 percent increase: this raised stock carrying capacity.

“Researchers also found that the most productive pastures in the worm trials had up to 7 million worms per hectare, weighing 2.4 tonnes. There was a close correlation between pasture productivity and total worm weight, with some 170 kg of worms for every tonne of annual dry matter production.”

How to Help Earthworms Thrive

Despite all earthworms do to improve soil productivity, they thrive best under specific conditions. Creating the proper habitat for earthworms can greatly increase their numbers and, in turn, create more productive soil. Unfortunately, much of what we have done in the form of soil management in the past has been quite detrimental to earthworm populations.

To enhance earthworm populations through management practices:

- **Don't till.** Ever. Tilled soil is quite inhospitable to earthworms. It kills them directly, it destroys their tunnels, it buries their food, and it exposes them to sunlight.
- **Keep the soil covered at all times with plant residue.** Ultraviolet light in sunlight is quite harmful to earthworms. Worms also prefer to eat their food on the soil surface. They cannot do this if the food is buried.
- **Supplement the worms' food supply** by adding cover crop residue to the residue of annual cash crops.
- **Be sure the food has enough protein.** Crop residues, like cornstalks and wheat straw, are almost always too deficient in protein for adequate earthworm nutrition. Using cover crops, particularly legumes, can help balance the diet for worms.
- **Provide an adequate supply of calcium.** Earthworms have an unusually high requirement for dietary calcium. Inner organs secrete into the digestive tract a high-calcium liquid that creates a habitat for rock-digesting microbes. Adequate calcium can be provided by either a diet high in legume

residue or an application of ground limestone (if needed to raise soil pH) or gypsum (if pH is already neutral).

- **Ensure adequate moisture.** If overhead irrigation is available, it can be a great asset to worm populations. If not, maintain adequate residue cover, and give high priority to all the other measures used to maintain soil moisture (discussed in Chapter 4).
- **Allow adequate oxygen content.** Low oxygen kills worms. Proper internal soil drainage is essential. Tile drainage may be useful if standing water occurs often and for long periods of time. Deep-rooted crops with aerenchyma tissue, like eastern gamagrass or reed canarygrass, are useful for boring holes through oxygen-limiting layers and improving internal drainage. Any vegetation tolerant of poor drainage, like annual ryegrass or ladino clover, will help by growing roots into the soil for eventual oxygen passages. Remember, the purpose of drainage is not to remove water; it is to ensure adequate soil oxygen.
- **Avoid pesticides that are toxic to earthworms.** Most herbicides and fungicides have little to no direct effect on earthworms, but some insecticides are toxic, particularly soil-applied carbamates and organophosphates. Pyrethroid insecticides are typically safe. Nematicides and fumigants are usually quite toxic to earthworms.
- **Graze with livestock, particularly cattle.** Cowpies make excellent earthworm feeding sites, as they offer not only food but also insulation from weather extremes. The soil immediately below a cowpie is cooler in the summer than

surrounding soil that is exposed to sun and warmer in spring and fall. The hoof traffic also tramples vegetation into soil contact, so it is accessible to earthworms.

- **Add compost or other imported organic materials,** such as lawn clippings, for additional worm food. Spread these on the surface in thin layers. If deposited too thickly, the decay uses up all the soil oxygen. Many small and frequent applications are better than occasional heavy applications.

How an Alligator Helped Save Citrus

EDWARD JAMES, Howey, Florida

I've always taken it for granted that I can have a big glass of orange juice every morning. But the US citrus industry now faces a dire threat that should deeply concern all citrus lovers.

Huanglongbing (HLB), a bacterial disease also known as citrus greening, is spread by the Asian citrus psyllid, a small insect. Once a tree is infected, its vascular system plugs up, the fruit remains unripe and bitter, and the tree loses vigor and eventually dies.

HLB appeared a few years ago in Florida, spread rapidly, and now threatens to wipe out citrus worldwide. The first approach was to bombard the orchards with insecticides, killing the psyllid before it spread the disease. This was expensive, though, and ineffective: The trees became infected anyway. Even pricier measures have failed, and HLB has marched along, devastating the entire Florida peninsula.

But one citrus grower may have found a solution to citrus greening, inspired by an enormous dead alligator. Edward James's orange grove near Howey, Florida, was nearly dead a few years ago. The "expert" advice was to

practice “sanitation” and “weed control” by keeping the orchard floors free of plant growth and debris.

This meant depriving the soils of the tree leaves and twigs and the vital root exudates from understory vegetation that form soil organic matter and feed soil microbes. Eventually the soils became lifeless and sterile. It is now increasingly suspected that this sterility predisposed citrus plants to HLB.

Edward and other growers also noticed that trees were much less affected by the HLB if they grew *with* vegetation; and that heavy doses of nitrogen fertilizer seemed to make HLB symptoms worse. But only when Edward’s kids shot and killed a 12-foot alligator did true inspiration strike him. After they butchered the animal for meat, Edward took a skid loader and buried the remains in his orchard—which was almost dead from HLB.

Subsequently he observed that although even the cover crops were stunted—growing only 6 to 8 inches tall in the thin, sandy soil with scant organic matter—the exception was where he buried the alligator! There they grew 3 to 4 feet tall, dark-colored and vigorous. More importantly, nearby trees seemed much less affected by the HLB.

Then it struck Edward: The solution to HLB is not some silver-bullet spray for the trees; it is in the soil itself. He reversed the “sanitation” trend and took the exact opposite route, increasing soil organic matter and biology. Of course, burying an alligator every few feet in the orchard was impractical, and compost too expensive. The solution: continue planting cover crops in the orchard to grow more

organic matter in place, supplementing with whatever organic materials he could, such as wood chips.

The results have been surprisingly good and seem to improve every year. Where Edward's trees were almost dead when he began, his citrus yields now approach what they were pre-HLB. His soil organic matter levels have gone from nearly zero up to a range of 3 to 5 percent, almost unheard of in the sandy soils of hot Florida.

And his out-of-pocket input costs are now a third of what is typical in citrus. He no longer sprays insecticide and uses very little herbicide; instead, his oranges have a vigorous understory of cover crops. Many of these are nitrogen-fixing legumes, greatly reducing his need for fertilizer.

Edward has been so successful with cover crops that he now promotes them to other citrus growers.

Dung Beetles

Dung beetles are my favorite animal, not only because we have so much in common, but because of the significant benefits they bring to soil; in this they rival earthworms. Dung beetles function primarily in pasture ecosystems and live by consuming manure. Dung beetles offer the following benefits:

Reduced manure fouling of forage. Animals refuse to graze close to their own feces. In a pasture that is stocked heavily, this can mean a very high percentage of the forage will be refused. It is estimated that at a stocking rate of one cow per acre for a five-month period, 15 percent of the pasture surface will be covered by cowpies. Cowpies prevent sunlight from reaching the underlying forage, and the forage in the immediate area around cowpies is refused by grazing cattle. Dung beetles can quickly bury a cowpie, to the benefit of the pasture and grazing animals. When the feces is buried, the forage becomes palatable sooner, and the underlying forage is exposed to sunlight sooner and able to begin regrowth sooner.

Improved distribution of nutrients. Dung beetles, particularly the rollers (the species that form manure into balls and roll them away and bury them), move manure away from the area where it is deposited and thus spread the fertility from a dung pat over a much larger area. (See Figure 3.1.)

Improvement in soil fertility. Typically, about half the nitrogen in manure is volatilized into the air within a few days of deposition. Dung beetles bury manure and prevent much of this loss. They also place manure into the soil where roots can access the immobile nutrients, like phosphorus, which is often a limiting growth factor in pasture ecosystems.

Reduction in internal parasites. Intestinal parasites lay eggs that infest dung pats, from which the larvae hatch and crawl onto surrounding plants to infect another animal. Dung beetles consume part of these eggs and bury manure deep

enough that the larvae cannot reach the soil surface. Research has shown that this can greatly reduce the number of infective larvae on a pasture.

Reduction in parasitic flies. Many species of pest flies lay eggs in manure. In the US, two pest species of cattle in particular lay eggs in fresh dung pats: the horn fly and the face fly. Between consumption and burial, dung beetles can greatly reduce populations of these flies (see table).

Improved water infiltration. Through their tunneling action, dung beetles create large pore spaces in soil into which rainwater can easily penetrate. A study in New Zealand demonstrated a 49 percent reduction in runoff during extreme rainfall events and an 81 percent reduction in runoff during moderate rainfall. Other research corroborates this effect, as seen in the table.

Improved oxygen infiltration. This results in deeper roots (see table opposite).

Overall increased pasture production. Obviously, better water infiltration, rooting depth, and nutrient availability and distribution would be expected to increase pasture productivity, and research indeed confirms that they do, as seen in the table.

Dung beetles can quickly bury a cowpie, to the benefit of the pasture and grazing animals.

HOW DUNG BEETLES IMPROVE PASTURES

Pasture Fly Populations

NUMBER OF BEETLES PER DUNG PAT	NUMBER OF FLIES EMERGING
Zero	23.2
2 pairs	13.9
8 pairs	1.5

SOURCE: B. M. Doube, A. MacQueen, and H. A. C. Fay, "Effects of Dung Fauna on Survival and Size of Buffalo Flies (*Haematobia* spp.) Breeding in the Field in South Africa and Australia," *Journal of Applied Ecology* 25 (1988): 523–536.

Pasture Water Infiltration

	RANGE OF MEAN WATER INFILTRATION RATES
Control (no dung beetles)	39.4–60.22%

SOURCE: J. Brown, C. H. Scholtz, J-L. Janeau, S. Grellier, and P. Podwojewski. "Dung beetles (Coleoptera: Scarabaeidae) can improve soil hydrological properties," *Applied Soil Ecology* 46, no. 1 (2010): 9–16. http://dx.doi.org/10.1016/j.apsoil.2010.05.010.

Pasture Water Infiltration

Dung Beetle Treatment	75.2–83.31%

SOURCE: J. Brown, C. H. Scholtz, J-L. Janeau, S. Grellier, and P. Podwojewski. "Dung beetles (Coleoptera: Scarabaeidae) can improve soil hydrological properties," *Applied Soil Ecology* 46, no. 1 (2010): 9–16. http://dx.doi.org/10.1016/j.apsoil.2010.05.010.

Soil Oxygen Content

	WITH DUNG BEETLE SPECIES *COPRIS OCHRIS*	CONTROL (NO DUNG BEETLES)
Air Exchange Rate	.56 cm/hour	.38 cm/hour

SOURCE: H. S. Bang, J-H. Lee, O. S. Kwon, Y. E. Na, Y. S. Jang, and W. H. Kim, "Effects of paracoprid dung beetles (Coleoptera: Scarabaeidae) on the growth of pasture herbage and on the underlying soil." *Applied Soil Ecology* 29 (2005): 165–171.

Pasture Productivity

SOURCE: G. T. Fincher W. G. Monson, and G. W. Burton, "Effects of cattle feces rapidly buried by dung beetles on yield and quality of coastal bermudagrass," *Agronomy Journal* 73, no. 5 (1981): 775–777.

Pasture Productivity

TREATMENT	PASTURE DRY MATTER YIELD (KG/HA)
Dung alone (contained 224 kg/ha N)	6,364
Dung (contained 224 kg/ha N) plus dung beetles	7,791
112 kg/ha N applied as ammonium nitrate	5,369
224 kg/ha N applied as ammonium nitrate	8,305

SOURCE: G. T. Fincher W. G. Monson, and G. W. Burton, "Effects of cattle feces rapidly buried by dung beetles on yield and quality of coastal bermudagrass," *Agronomy Journal* 73, no. 5 (1981): 775–777.

How to Encourage Dung Beetles

You can improve dung beetle populations with a few different strategies:

- **Maintain nutritious pasture.** The more nutritious the pasture, the more nutritious the dung will be for the beetles.
- **Use rotational grazing** to concentrate the animals so that their dung is also concentrated, and the beetles can find fresh dung more easily.

- **Avoid the use of systemic insecticides** that are known to cause harm to dung beetles, at least during the growing season when dung beetles are active, and at least a month prior to the start of dung beetle activity in the spring. Probably the worst of these products as far as dung beetles are concerned is ivermectin.
- **Finally, do not till land** where dung beetles have laid eggs.

Microbes

I heard the following story about a farmer in western South Dakota (as told by one of the people involved). He farmed in a 16-inch rainfall area where wheat–fallow–corn–fallow was the common rotation, with two crops raised in three years, and roughly 11 months of fallow between one harvest and the next planting.

At some point, this farmer began replacing the long fallow periods with a cover crop of peas, and his yields went up 23 percent (confirmed by USDA investigation) compared to the same rotation without the cover crops. He asked a USDA person why this was so; the explanation was that the peas were a legume and contributed nitrogen to the system.

He then asked why adding more nitrogen fertilizer did not accomplish the same yield bump. The answer was that he must be creating a better mulch that holds more moisture. Yet upon measurement, the moisture levels in both systems were found to be the same. The cover crop used moisture, but the mulch it generated increased infiltration of following rainfall and

reduced evaporation so that the net soil moisture content was the same by planting of the next crop.

This puzzle continued until the USDA soil microbiologist inspected the soil and found an astonishing *700 times* more microbes than the system without the pea cover crop. That is such an incredible difference that it is, at first glance, a bit hard to swallow. But anyone who has ever fed cattle (or any other ruminant) can easily understand how this could be true.

The rumen is a big fermentation vat, just as the soil is a big fermentation vat. If you feed a herd of cows nothing but cornstalks and wheat straw for a year, they would probably not successfully raise a single live calf. If this continued for a century, there would be no herd at all.

Tea Lesson

Sir Albert Howard, an early leader in the organic farming movement, was a plant pathologist for the British government in India during the early part of his career. One of his primary tasks was to learn how to manage diseases in the tea crop. This was critical business because, after all, the British Empire did run on tea.

Conventional wisdom said that the way to manage disease was through strict sanitation, to remove all residue and have a completely bare soil between growing seasons to eliminate the source of infection. Yet this alone was found completely ineffective, so Sir Albert proposed selecting

more disease-resistant plants and breeding them to make more tolerant tea plants. He then deliberately tried to infect tea plants (so he could select the survivors for breeding) by mulching them with the diseased leaves from the previous crop, which had been laboriously raked into piles.

To his astonishment, he could not induce disease in this manner, and instead found that the mulched plants were much less affected by disease than the plants in the cleaned areas. Confused, he looked at the mulch through microscopes and found that *the residue piles had formed a culture of microbes that ate the disease organisms of tea*. The mulch acted as a probiotic.

If you have read Sir Albert's works, you know that this is a gross oversimplification of the story, and I apologize for the liberties I have taken to put it into concise form. If you have not read his works, I would begin with *An Agricultural Testament*.

Underlying this would be a gross deficiency of protein in the diet, since rumen microbes require a minimum of 7 percent protein in order to survive, and maintaining any level of production requires 12 percent protein. Wheat straw is 3 percent protein, and cornstalks only slightly better, which is not enough protein to reproduce for microbes; that is, except for the pathogens that evolved to live on crop residue.

A diet of nothing but cornstalks, wheat straw, and soybean stubble will eventually starve your herd of underground livestock just as it would aboveground livestock.

The Kill ’em All Approach

If you walk through a typical supermarket, virtually every aisle will contain items with boldly colored tags that say “antibacterial.” Since some bacteria are bad, the strategy is to kill them all, just in case. The result of this widespread practice is that we have not only eliminated huge numbers of beneficial bacteria but have also weakened human immune systems. The elimination of benign bacteria means that the immune system is not challenged enough to develop antibodies to those bacteria, and when a truly bad microbe is introduced to the body the immune system is completely unprepared.

We have in the past approached crop production in a similar manner. It has been common practice to burn residue, or to plow deeply, or sometimes both, attempting to control plant disease, particularly in areas where continuous wheat is the standard “rotation.” While this was initially somewhat effective at controlling residue-borne disease, it also resulted in a rather sterile soil. The total lack of microbes means that residue is not naturally decayed, and thus pathogens have host material in that form for an unusually long time.

Perhaps this is why we are now seeing such disease issues in our corn–soybean rotations over so much of the country. We have a very short, agronomically unsound rotation being conducted on soils that have no active biology to decay the

residue. Thus, the pathogens that inhabit corn residue, like Goss's wilt, survive for more than a growing season, as do the pathogens that infect soybean residue. In a soil with a healthy biology, residue disappears quite rapidly, and residue-borne diseases cease to become an issue. (See Chapter 9 for more discussion on the pitfalls of the corn–soybean rotation.)

Microbiologists are known to recite a poem that reads:

The bugs that bite us have bugs that bite 'em

And even those have ones that bite 'em,

And so on and so on, ad infinitum.

Every living organism is part of a food chain; everything is eaten by something (except embalmed humans in sealed coffins that keep the plant nutrients of our bodies from returning to the cycle of life).

Restoring Microbial Populations

Our soils have been tilled and fallowed and sunbaked for so long that they are now almost devoid of microbial life, except for the pathogens inhabiting the crop residue on which they like to feed, facing no competition or predation by other microbes.

I was taught that inoculating soils with microbes was useless; however, our soils are now somewhat like a pond that has dried up. If you refill it, you still will have no fish because there are no parent fish there to begin with.

While our soils do contain microbes, they may not be the ones we want. Some of our microbe species are so scarce that they may as well be considered locally extinct and may have to be reintroduced. But first, the conditions must be made right for them to thrive after reintroduction. In other words, fill the pond with water *before* putting in the new fish.

In a healthy soil, pathogens are almost always present, but they are seldom a major issue, for a couple of reasons. First, since they are part of the food chain themselves, there are usually plenty of organisms to eat them if they begin to become abundant. Second, since most pathogens survive the period between host crops by living on infected crop roots or residue, an active set of saprophytes removes the food source for the pathogens.

As an example, one of the most destructive corn diseases in Nebraska is Goss's wilt. It is caused by a bacterium, so fungicides are completely ineffective. And since the bacteria survive on infected corn residue, the disease is particularly bad in continuous corn. At one of the major seed corn companies in Nebraska, however, researchers noticed that the small area where they had sown a cover crop of rye the previous fall had no Goss's wilt, even though it was in continuous corn.

How did the rye help? Possibly it was because the rye residue prevented rainfall from splashing soil particles containing the bacteria onto the leaves. But I believe it was because the rye was killed while still in a lush vegetative state (thus high in protein), and the residue covered the corn residue, providing a nutritious, protected substrate for

saprophytic organisms to simply eat both the Goss's wilt bacteria and the corn residue it depended on.

I have heard of many people who planted a cover crop of some brassica, such as radishes, into wheat stubble and noticed that the wheat stubble was completely rotted in spring, though wheat stubble without a cover crop was still present. The high-protein residue from the brassica leaves gave the microbes what they needed to break down the straw. If residue from crops grown more than a year previously are still recognizable on the soil surface, it indicates a severe lack of soil biological activity, and that soil biology must be restored for optimal soil function.

Three Types of Microbes

There are three broad groups of microbes in the soil based on general function. Microbiologists would probably categorize them into bacteria, fungi, protozoans, actinomycetes, and so on, but I prefer to classify them by the jobs they perform:

1. The first group occupies the area immediately surrounding the root, called the **rhizosphere**. The rhizosphere organisms live off root exudates, which means they need live roots in the soil in order to survive.

2. The second group is the residue-decaying organisms, or **saprophytes**, that live off dead plant or animal residue.
3. The third group is composed of **pathogens** that actually eat the plants.

ESSENTIAL STEPS TOWARD RESTORING MICROBIAL POPULATIONS

Here are the key steps and principles to take in order to enrich your soil with beneficial microbes.

No tillage. Ever. Tillage is destructive on so many levels that it should never be a consideration if your goal is better soil.

Keep the soil surface covered at all times. Ultraviolet light is a great sterilizer. You can purchase little devices at outdoor supply stores that emit a beam of concentrated ultraviolet light into a container of water and kill all potential pathogens.

Sunlight striking bare soil accomplishes the same thing, except most of the microbes killed are beneficial. Additionally, on a hot summer day the temperature of bare soil can reach over 140°F. Ironically, that is the temperature above which we want the interior of our Thanksgiving turkey to reach, in order to (you guessed it) kill potentially pathogenic microbes.

Keep live roots in the soil at all times when the soil temperature is above 50°F. Perennial crops can provide living

roots for 12 months a year. In the absence of perennials, inclusion of cover crops into rotations of annual crops can potentially achieve this goal.

Many, if not most, of the beneficial organisms in the soil are rhizosphere inhabitants, and they require a live root in order to survive; there is no substitute. Research has shown that most of the contribution to soil organic matter comes from microbes fed by root exudates, not the decay of plant residue.

Add organic materials to the soil surface. A continuous supply of surface-applied organic material with sufficient protein content and moisture will allow for microbial growth. Animal manure is an ideal substrate, but a mulch of crop residue or cover crop residue of sufficient protein level can be a partial substitute.

Inoculate with desired microbes. It makes sense to introduce the microbes you want rather than rely on the random chance that those voids will fill with desirable organisms. In my experience, ponds that have not been stocked with largemouth bass, bluegill sunfish, and channel catfish seem to somehow always end up with a population of undesirable and (at least to my palate) inedible carp and bullhead catfish.

Sterile soils that suddenly receive large inputs of crop residue will likely develop large numbers of pathogens, at least initially. Inoculating with the right microbes can get a healthy population established from the start.

INOCULATING WITH COMMERCIALLY AVAILABLE MICROBES

First, let's make one thing clear: You cannot simply inoculate your way to healthy soil. If you do not first create the conditions in which beneficial microbes can thrive, inoculating with commercial microbes (or any microbes) can be a waste of money. Without a system in place, a "bugs in a jug" product is likely to be of very limited value. But that does not mean these products are completely useless; it just means that they need to be part of a comprehensive program that will allow them to reproduce and thrive over time.

There are folks who universally dismiss the validity of any microbial inoculants, but still believe in inoculating legume crops with the proper *Rhizobium* bacteria for nodulation and nitrogen fixation, because they know their soils are likely deficient in that bacteria. Why are other microbes any different?

So what microbes are the right ones with which to inoculate, and how does a person obtain them? One way to obtain microbes is to buy them. Following are some suggestions of commercially available inoculants. Bear in mind that this list is by no means complete. There are many other beneficial microbes, and more are being discovered and developed all the time.

The microbes described here are ones I have personally used (or know people that have) with very satisfactory results. Not all products are legitimate, and none of them is a miracle yield booster. They will provide yield increases when some growth factor is supplied to the plant that was not there before, or

when some disease or pest is suppressed that was not suppressed before. And remember, before you buy microbes, take necessary steps to establish all the conditions in the list starting here.

MYCORRHIZAL FUNGI

First on my list of microbes to consider purchasing are mycorrhizal fungi (MF), because they are so often lacking in cropland soils and so slow to recolonize on their own. MF make up a class of symbiotic fungi that colonize plant roots and aid plants in the uptake of water and nutrients. (See Figure 5.5.)

Drought tolerance. Primary among the benefits of MF is increased drought tolerance, largely due to the ability of mycorrhizal hyphae to greatly expand the root zone beyond the roots themselves. (See Figure 3.3.) Hyphae are 1/17 the diameter of root hairs and can reach into soil pore spaces too small for roots. They also cause actual physiological changes in colonized plants and improve drought tolerance.

Mineral uptake. MF are also a huge help in the uptake of mineral nutrients, particularly immobile nutrients such as phosphorus and zinc. The table below illustrates the improved nutrient uptake of colonized plants. This benefit is important for improved plant growth, of course, but perhaps more important for improved nutritional quality for the livestock and humans consuming the plants.

Root protection. Mycorrhizal fungi coat plant roots with a polysaccharide called **chitin** (the same compound that makes up crab shells), which root pathogens and nematodes have a hard time penetrating.

Weed control. Many weed species, key among them members of the *Amaranthus* genus (pigweeds), are not colonized by MF and thus do not enjoy their benefits. Inoculating a crop that does benefit from MF makes the crop roots more competitive for water and nutrients than the weeds. Obviously, this does not kill weeds, but it slows their growth rate, which makes them easier to control and reduces their impact on crop yield. The table illustrates the effect of MF on weed control.

Glomalin production. Finally, as discussed in Chapter 3, MF secrete a compound called glomalin, a biological glue that creates soil aggregates. Glomalin is arguably the most persistent biological glue and its effects on soil structure are quite striking.

HOW MYCORRHIZAL FUNGI AFFECTS MINERAL CONTENT IN TOMATOES*

NUTRIENT	NONSALINE SOIL	SALINE SOIL

*Percent increase in content

SOURCE: G. N. Al-Karaki, "Nursery inoculation of tomato with arbuscular mycorrhizal fungi and subsequent performance under irrigation with saline water," *Scientia Horticulturae* 109 (2006): 1–7.

HOW MYCORRHIZAL FUNGI AFFECTS MINERAL CONTENT IN TOMATOES*

Phosphorus	44	192
Potassium	33	138
Copper	93	193
Iron	33	165
Zinc	51	120

*Percent increase in content

SOURCE: G. N. Al-Karaki, "Nursery inoculation of tomato with arbuscular mycorrhizal fungi and subsequent performance under irrigation with saline water," *Scientia Horticulturae* 109 (2006): 1–7.

What Happened to All the MF?

Mycorrhizal fungi are ubiquitous in virtually every terrestrial natural ecosystem but are nearly extinct in most cropland. Why? MF fungi coevolved with perennial plants and die when there is no living root as a host. Replacing perennial plants with annual crops resulted in fallow periods during which the MF starved out.

To make matters worse, long fallow periods were adopted in arid areas to store soil moisture. This was initially

successful in improving dryland crop yields but ended up starving out the mycorrhizal fungi, which were our biggest allies in providing drought tolerance.

This, however, is avoidable. Land seeded down to perennials, such as perennial forage grasses, will have living roots for 12 months of the year. Use of cover crops to replace fallow in crop rotations allows for a living root most of the year to host MF, even in cropland devoted to annual crops. Since most cropped soils lack MF altogether, an initial inoculation is often necessary.

Some of the more important MF species include:

- *Glomus intraradices*
- *Glomus fasciculatum*
- *Glomus aggregatum*
- *Glomus mosseae*
- *Glomus deserticolum*
- *Gigaspora gigantea*

These species are all **endomycorrhizal** fungi (meaning they penetrate into plant cells) and colonize most herbaceous crops as well as many woody species.

A different class of MF called **ectomycorrhizal** fungi (meaning they do not penetrate plant cells) colonizes several species of woody plants, such as oaks, pecans, hazelnuts and pines (see the list at right).

Plants Colonized by Endomycorrhizal Fungi

- Corn, sorghum, wheat and other small grains, and all other grass crops including forage grasses
- Sunflowers, potatoes, sweet potatoes, strawberries, onions, okra, carrots, cotton
- Alfalfa, clovers, soybeans, and all other legumes except lupine
- Citrus
- Stone fruits (peach, cherry, plum, almond)
- Grapes
- Caneberries (blackberries, raspberries)
- Pome fruits (apples, pears)

Hosts for Ectomycorrhizal Fungi

- Oaks
- Pines and other conifers
- Hazelnut
- Beechnut
- Chestnut
- Eucalyptus

Hosts for Both Ecto- and Endomycorrhizal Fungi

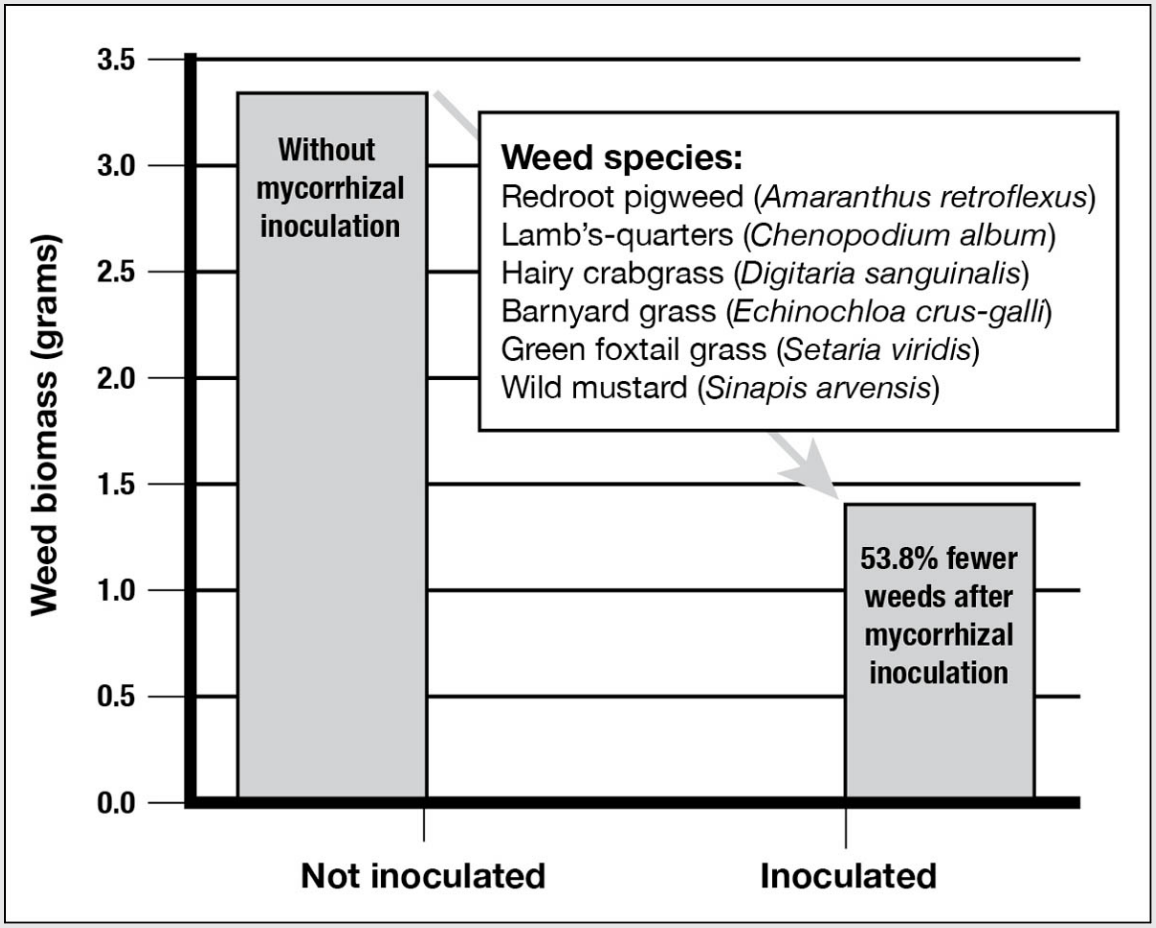
- Poplars, including cottonwood
- Willows

- Hickories

Nonhosts for Mycorrhizal Fungi

- Brassicas: kale, cabbage, broccoli, canola, mustards, turnips, radish
- Polygonaceae: buckwheat, smartweeds
- Chenopods: spinach, sugar beet, lamb's-quarters
- Amaranths: pigweed, water hemp, amaranth
- Sedges and rushes

Suppression of Aggressive Agricultural Weeds by Mycorrhizal Fungi with Sunflowers



STREPTOMYCES LYDICUS

A microbe that is classed as a biofungicide, *Streptomyces lydicus* is marketed under the trade name Actinovate. (It is

related to the organism from which the antibiotic streptomycin was derived.) In addition to its ability to control numerous plant pathogenic fungi and bacteria (both in the soil and as a foliar spray), it is also effective at producing **siderophores**, compounds that dramatically improve iron availability in the soil.

In the many areas of the country with high-pH calcareous soil that suffers from iron deficiency chlorosis, this could cause an improvement in iron availability. Soybeans and sorghum are two plants that are quite susceptible to iron deficiency chlorosis. *S. lydicus* is combined with an iron fertilizer and marketed under the trade name Actino-Iron. This organism is as effective as many chemical fungicides and has the added bonus of controlling many pathogenic bacteria, which most chemical fungicides do not.

AZOSPIRILLUM

A bacteria that inhabits the rhizosphere of plants (the area immediately surrounding the roots), *Azospirillum* offers some potentially large benefits to plants. Perhaps foremost is the ability to fix nitrogen without the need of a legume as a host plant. As long as the plant exudes sugars, *Azospirillum* seems to do well. Some research indicates *Azospirillum* may fix as much as 80 pounds of nitrogen (N) per acre, although the typical amount fixed is much less. In addition, *Azospirillum* produces plant growth hormones that dramatically increase early root development.

Worldwide, there are more acres treated with *Azospirillum* than with *Rhizobium* and *Bradyrhizobium* (the nitrogen-fixing

bacteria on legume roots), but virtually no acres in the US. Why? Because the amount of N fixed is usually insufficient for profitable yield levels, and if additional N is applied, then the *Azospirillum* doesn't fix any. It is only in conditions of low available nitrogen that *Azospirillum* shines, and that is a rare situation in US agriculture.

In some situations, however, *Azospirillum* can be very useful. One is when the primary source of nitrogen fertility is slowly available, such as the residue of a previous legume crop. This is common in organic farming, where soluble nitrogen fertilizers are not allowed. The other situation is when it appears in blends of legumes and other plants, such as cover crop blends and grass-legume pastures.

These mixtures are usually not supplied with nitrogen, so the legumes are forced to fix nitrogen. Addition of *Azospirillum* turns all the plants in the mixture into potential nitrogen fixers, perhaps enhancing the nitrogen production capacity of the blend enough that it can supply all the needs of the following crop.

Although *Azospirillum* has tremendous promise, it is a fragile organism (similar to *Rhizobium* bacteria) and is easily killed by heat, ultraviolet light, and drying. It also seems to be better adapted to tropical conditions than temperate. Despite these limitations, I have seen very good responses to inoculation with *Azospirillum* and the similar *Azotobacter* (described below).

AZOTOBACTER

Azotobacter is a free-living nitrogen-fixing organism quite similar to *Azospirillum*, with perhaps less fixation capacity, but it is less fragile. Adding *Azotobacter* along with *Azospirillum* increases diversity and resilience of the free-living microbial population.

BACILLUS SUBTILUS

This microbe has an interesting history, or maybe myth, behind it. The story goes that *Bacillus subtilus* was identified by the German Army medical corps during World War II in North Africa. More Germans were dying of dysentery than from British bullets, yet the Egyptians who were drinking the same water were unaffected. When the Germans asked why the Egyptians did not get dysentery, the Egyptians replied, "Because we eat camel dung when we are sick."

I can only imagine what the Germans thought: "This must be the story they tell the tourists to see whether they try it, then they laugh behind their backs if they do try it." But the German scientists examined the camel dung and found large numbers of a bacteria that actually would eat the organisms that caused dysentery. This bacteria was later developed into one of the first successful probiotics cultured by science.

Bacillus subtilus eats a wide range of microbes, many of which are plant pathogens, such as *Fusarium*, which causes root rots and stalk rots of corn and head scab of wheat. *Bacillus subtilus* is registered by the EPA as a biofungicide and is found in several commercially available forms.

PAENIBACILLUS POLYMYXA

The source of the commercially available antibiotic Polymyxin B, found in triple antibiotic creams such as Neosporin, *Paenibacillus polymyxa* can colonize the surface of plant roots and form an antibiotic layer that prevents bacterial pathogens from entering the roots. Because tomato bacterial wilt, the scourge of tomato growers everywhere, is caused by a bacterium that enters the roots, *P. polymyxa* may be particularly useful in tomato culture. This organism is also found in several commercial inoculants.

The story goes that Bacillus subtilus *was identified by the German Army medical corps during World War II in North Africa.*

Beware of simple side-by-side trial results. If you split a field in half and do absolutely nothing different between the two halves, one side will yield more than the other.

TRICHODERMA

Trichoderma are several species of fungi that parasitize several pathogenic fungi, such as *Pythium*, which causes seedling blights. Cornell University has actively researched and commercially released a strain called T-22. A species of *Trichoderma* is also a component of the microbial corn inoculant marketed as QuickRoots. *Trichoderma* exudes plant hormones that speed root development. They are fairly

effective at preventing many forms of root diseases from becoming a problem.

BACILLUS PUMILUS

Active against many root pathogens, including *Rhizoctonia* and *Fusarium*, *Bacillus pumilus* is marketed as the EPA-registered biofungicide Sonata. It also suppresses the wheat disease take-all (caused by the fungus *Gaeumannomyces graminis*) and appears capable of fixing small amounts of plant-available nitrogen in the rhizosphere.

JUMPSTART

A phosphate-solubilizing fungus, JumpStart (*Penicillium bilaiae*) is effective at freeing phosphate from calcium phosphate compounds like those found in calcareous soils (soils with a high pH and excess calcium carbonate or limestone). JumpStart is usually of no benefit in acidic soils.

Comparing Commercial Microbial Inoculants

Many agronomists and horticulturists are understandingly skeptical of using “bugs in a jug” microbial inoculants. There certainly is no shortage of such products, and not all of them are *good* products. Determining which products will give the desired results from ones that do not may be difficult. Following are some tips for comparing commercial microbial inoculants.

CHECK THE CFU COUNT

One good means of comparing products is to look for the number of colony-forming units, or CFUs, per unit of measure. I once looked at two such "bugs in a jug" products that at first glance appeared to be almost identical. Then I looked at the CFUs per unit measure. One had a concentration of 10,000 CFU per ml; the other had 10,000,000 CFU per ml. That is a difference of a thousand-fold more organisms in the second product than the first. One sold for $8 a gallon and the second sold for $20 a gallon. Which was the better deal?

LOOK AT THE ORGANISM TYPES

Another means of comparison is to see which types of organisms the product contains. I absolutely do not trust "secret ingredients" or "proprietary" organisms. If the organisms and the CFUs are not on the label, do not buy. If the organisms are labeled, it is a simple matter to do your own research on the internet of the legitimacy of those organisms.

EVALUATE THE RESEARCH

When looking for scientific support of specific organisms, focus on independent third-party research. Universities are not the only research institutions around, but they are often among the least biased (unless the manufacturer donates generously to the university). Consider the experimental design. The key factors to look for are replication, no-treatment controls, and randomization.

Beware of simple side-by-side trial results. If you split a field in half and do absolutely nothing different between the two halves, one side will yield more than the other. If you put out a hundred side-by-side trials, random odds will give you fifty "wins." All you need to do to make an impressive brochure is to cherry-pick the results of the more impressive "wins."

I once did a demonstration at a university training event. It involved four rows of corn. On the two western rows there was a sign reading, "Experimental product applied to these two rows." I then had all the participants file by and tell me how much they would pay for the product applied to those two rows. The average answer was $8 an acre. When the plot tour concluded, all the participants wanted to know what the experimental product was. I told them the truth: I applied *nothing* to those two rows. I just picked out the two rows that looked better, and I wanted to see how much they were willing to pay for nothing.

The point I wanted to make was that a side-by-side comparison may be favorable because it is a legitimate product, or it may be favorable because it was applied to the part of the field that was going to yield more anyway. That is why replication and randomization are so important to experimental design. A hundred side-by-side trials are useful information but only if the data from all one hundred trials are included, not just the ones that showed a favorable response.

LEARNING BY DOING

Grow Your Own Microbe Inoculants

One of the best ways to obtain beneficial soil microbes is to culture your own, such as in compost extracts and compost teas (see Chapter 6). A home-brewed concoction will not give you a guaranteed analysis or a CFU count (unless you are really, really knowledgeable and good with a microscope), but the price is certainly right, and, if done correctly, experience shows very good results from using these products from well-made composts.

Sources of good microbes for making your own inoculants can be as nearby as a forest floor or a pristine prairie. One fall day a few years ago I was planting rye in the field next to my house. The day was brutally hot, and I chose to fill the drill in the little woodland behind my house where there was shade. I spilled some seed during the filling process, and the seed sprouted on the forest floor.

The next spring, the rye in the field (where I did everything I could to make it grow) was waist-high. The rye I spilled on the forest floor (and did absolutely nothing for) grew to 7 feet tall.

That woodland has never, ever been fertilized in history. I don't know what unknown microbe or microbes there are in that woodland soil that made that rye grow like that, but

I know I want it in my field. With a properly made compost extract utilizing a bit of that woodland soil, I can make a product containing that unknown microbe and easily apply it on my field.

BEWARE FARMER TESTIMONIALS

Farmers believe farmers. People pitching products realize this and will use farmer testimonials quite often. You will never see a bad farmer testimonial. Getting a good farmer testimonial is quite easy. If a product manufacturer gives a farmer free product, that act incurs a sense of obligation from him to say good things about the product. If they put out a lot of trials, just by chance some will give good results even if the experimental design is lacking, as is the case with side-by-side trials.

It is a simple matter to interview only these farmers with the good results and splash their words across a printed brochure. What you will never see is the interview from the farmers who did not have good results, and you will have no idea how many of those there were.

It is easy to put out a hundred farmer trials, and only pick out the dozen or so that had the best results. I am not saying any of these farmers are lying. I am saying that you will only hear from the farmers who had very positive results, and never the ones who had little success or negative results.

Unofficial farmer testimonials—that is, reviews you hear from farmers firsthand—can have some value. Do not

completely discount anecdotal farmer evidence, but always maintain a certain level of skepticism.

DO YOUR OWN RESEARCH

Research is not limited to scientists or universities. Try a product on a limited scale, perform due diligence to replicate the trial multiple times, and try to control as many variables as possible, making the product the only variable between trials.

In the past, we have tried to fight plant diseases through a "scorched earth policy" of killing as much soil life as we could. While this initially works well, the void of microbial life soon gets filled, and usually not with the type of life we desire. I think that in the future we will focus more on creating soil conditions in which pathogens have a hard time getting established, and those that do are simply overwhelmed by beneficial microbes. Perhaps the motto of plant pathology in the future may be, "The best way to stop a bad microbe is with a good microbe."

Protein and the C:N Ratio

Microbes are made primarily of protein. Proteins are complex molecules composed of carbon, hydrogen, and oxygen, like all organic compounds, but they also contain nitrogen and sulfur. Other organic compounds, such as cellulose, starch, and lipids, do not contain nitrogen or sulfur. Microbes can use cellulose or starch for energy but require a certain amount of protein (or at least nitrogen and sulfur, for some microbes) in order to

reproduce. Plant residues contain cellulose, starch, and protein, as well as smaller amounts of lignin, lipids, and other biochemicals.

Of these compounds, protein is essentially the only one that contains nitrogen. A high ratio of carbon to nitrogen (C:N) essentially means that a residue is low in protein, while a low C:N ratio means that a residue is high in protein. A high-protein residue, like fresh green leaves, supplies adequate energy and protein, and the decay of it results in the release of excess nitrogen in plant-available forms—first as ammonium, then, as other microbes convert ammonium, as even more available nitrate. The historic term for such residues was *green manure*. Most legume residues and the early vegetative growth of most herbaceous plants fit into this category.

A low-protein residue (examples of which include most crop residues, such as cornstalks, wheat straw, mature dormant grass residue, and woody debris) has the opposite effect. The microbes have plenty of carbon but are short on protein (nitrogen). There is often an actual depression of nitrogen availability when low-protein residues are added to soil, especially if incorporated with tillage, as microbes will use plant-available ammonium or nitrate to help produce protein for reproduction. This is often seen in crops following sorghum, corn, and small grains such as wheat.

A ton of wheat straw incorporated into the soil will create the need for an additional 20 pounds of plant-available nitrogen. Sorghum roots and root exudates have a very high amount of sugars and a relatively low amount of protein, and therefore a very high C:N ratio. This helps explain why wheat

planted immediately after sorghum harvest usually yields much less than wheat planted immediately after soybeans or corn, unless additional nitrogen is supplemented to the wheat after sorghum.

It may be possible to convert the millions of acres of warm-season grasslands around the world into a much more productive condition in terms of protein per acre

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How to Make the Most of Low-Protein Residue

Another important feature of the decay of residue affected by the C:N ratio is that it takes a certain amount of nitrogen to form **humus**. If a residue is low in protein, it may not have enough nitrogen to form much humus. This helps explain why burning the residue of warm-season grass pastures does not reduce the organic matter level of grassland soils. Decades of research conducted in native tallgrass prairie sites have shown that the amount of soil organic matter in annually burned areas is equal to or greater than that of adjacent unburned areas, contrary to what might be expected. The residue is so low in protein that its decay would not reproduce much humus anyway. Clearing away the residue with fire allows new green leaves access to full sunlight, which offers more benefit than the small amount humus it would have produced. (See Figure 5.7.)

There is increasing interest, however, in new techniques designed to utilize this low-protein residue in combination with supplemental protein sources as a ruminant feedstuff during the dormant season. This can be used to replace expensive hay as a dormant season feedstuff. And by combining the low-protein grass residue with a higher-protein feedstock inside the animals' rumens, it can turn a residue that would not otherwise produce much humus into a manure pie that is highly effective at building humus.

One way to do this is to import high-protein supplemental feeds. Another method, which is more promising and likely more economical, is to interseed a cool-season legume to add high-protein forage to the forage mix and to provide an additional set of living roots into the soil during the time when there is no active photosynthesis by the dominant vegetation.

This is similar to the "pasture cropping" concept developed by Colin Seis and friends in Australia, in which cool-season grains (like wheat) are planted into dormant warm-season grass sods. This practice has been shown to dramatically increase soil organic matter, since it results in active photosynthesis and root growth over the entire year rather than just in the summer.

We have often assumed that the organic matter levels of native grasslands are as high as they are ever going to get; this may not be the case. Human intervention may actually be able to dramatically improve the organic matter of very old grasslands over time.

Given the degraded and rather unproductive state of much of the world's grasslands, the huge acreages occupied by them, and the typical poverty of the human population of those

grasslands, this is an exciting concept. It may be possible to convert the millions of acres of warm-season grasslands around the world into a much more productive condition in terms of protein per acre, while simultaneously sequestering huge amounts of carbon in the soil. Win-win all the way around.

Adding Nitrogen to Speed Decay

Adding nitrogen to a low-protein residue can greatly speed its decay and increase the amount of humus formed from it. In areas where continuous corn is the norm it is becoming increasingly common to spray a solution of nitrogen fertilizer along with a "sticker" to help it adhere to the residue and speed decay. This practice is intended to help recycle nutrients held in the residue and reduce disease pressure through host elimination. Unfortunately, research indicates this approach is not very helpful, perhaps because the residue is still exposed to ultraviolet light.

Another way of accomplishing a similar result is to seed a high-protein cover crop into a low-protein residue, particularly if the residue is grazed. As mentioned earlier, cornfields that have a winter cover crop have been found to have much lower incidence of Goss's wilt than identical adjacent fields without the cover crop, perhaps because the more active biology in the residue layer decays the corn residue that is the host for Goss's wilt.

Wheat stubble that has had brassicas seeded into it decays much faster than wheat stubble without, perhaps because

when the brassicas freeze down, the high-protein cell contents spill out onto the low-protein wheat residue, and the wilted leaves protect the underlying residue from ultraviolet light.

In short, understanding the C:N ratio and intelligent manipulation of the C:N ratio can enable the land manager to optimize both short-term crop yields and long-term soil improvement.

Fermentation Vats on Four Legs

The ideal environment for microbes is warm and moist and protected from ultraviolet light, and all the high-protein and low-protein materials are in very small particles and in intimate contact with one another to create a homogenous substrate with an ideal C:N ratio. Such an environment occurs only rarely on the soil surface. This is why the aboveground biomass of plants contributes so little to soil humus production relative to root exudates, though the aboveground biomass usually is several times greater in biomass than the root exudates.

If only there were a machine that could gather a mix of high-protein and low-protein materials; finely grind them; put them in a warm, moist, and dark fermentation chamber; then deposit a homogenous fermented soil-improvement material back on the surface! And while we are dreaming, what if this machine were entirely solar powered so it is even more

environmentally friendly? And how about we design it so that it has an attached 3-D printer that creates its own replacement?

To get really preposterous, let's make it 100 percent recyclable and 100 percent biodegradable and made of indigenously sourced materials. Better yet, let's make it recyclable into protein that humans can eat. Or maybe even human-edible protein that tastes so good that entire restaurant chains spring up to serve it.

As it turns out, there is no need to create such a machine. There happens to be one already that meets all these pie-in-the-sky design specifications. That is a ruminant animal, inside the rumen of which amazing microbial transformations occur and from which a powerful soil-improving material is dispensed: ruminant manure.

The Prairie and Its Soil-Building Inhabitants

The incredible natural fertility of the prairie was built by several factors: a favorable geology (glaciation); deep-rooted perennials (many with a C4 photosynthesis; see here); continual ground cover without soil disturbance; and last but not least, manure from large herbivorous animals that have fermenting digestive systems. These animals are bison, most recently, with mastodons, mammoths, camels, and horses in prehistory.

Animals with fermenting guts belong mostly to three major groups:

- ruminants, which include cattle, sheep, deer, goats, bison, buffalo, and antelope
- animals with a fermenting cecum (a pouch between the small and large intestine, analogous to the appendix in humans), such as horses, rabbits, and elephants
- plant-fiber-eating insects, such as termites

What these animals all share is the ability to derive energy from the world's most abundant organic compound: cellulose, the primary compound found in the cell walls of plants. No animal produces the digestive enzyme (cellulase) that breaks down cellulose. However, there are many microbes that produce this enzyme, and many of them are capable of inhabiting the digestive system of the three groups of animals mentioned.

Our Diet, Land Use, and Ruminants

The use of animals with fermenting digestive systems as a food source (though I'll skip the termites) can vastly expand the area of the world that can be used for agriculture. Obviously, much of the world's area is already being used in this manner, being grazed by fermenting herbivores, both wild and domestic. Those who recommend a vegetarian diet, based on the notion that eating lower on the food chain will free up more foodstuffs for humans, fail to take this biological reality into account. It is only when livestock are fed grain, as happens during the final few months of cattle in North America (and

with most pigs and chickens), that they are eating the same food as humans. This is *not* true with pastured ruminants.

Humans cannot derive massive amounts of energy from most of the world's land area as it exists now. It is too rocky, too dry, too salty, too icy, too prone to erosion, too something, to produce crops. Additionally, I have always thought it a bit anthropocentric and selfish of our species to destroy large areas of forests and prairies and deserts and convert them into sterile monocultures of crops, eliminating huge numbers of plants and animals in the process. An acre of soybeans destined for tofu kills far more animals through habitat removal than any slaughterhouse does.

Fortunately, we can get food from native ecosystems that *are* left intact through the miracle of the bovine rumen. On my own farm, I replaced a sterile corn–soybean field with a diverse pasture blend of grasses, legumes, and forbs, harvested by cattle (see Chapter 12). That type of restoration, however, is still rare. More often, the opposite happens, and every year more prairies are plowed and planted to crops.

Most of what was prairie in the United States has been sacrificed to the plow—as much as 98 percent, by some accounts. The organic matter levels are less than half of their original levels, and these areas are now growing corn, soybeans, and wheat. Some of these fields are still undergoing extensive tillage, though no-till is gaining ground (pun intended).

Often these soils are laid fallow for extended periods, growing nothing for months at a time. In a typical two-year corn–soybean rotation there is plant life for only 9 of the 24

months. Farther west, in corn–fallow–wheat–fallow areas, the soil may be devoid of growing plants for 22 months of a three-year rotation.

Landowners often refuse to allow livestock, particularly cattle, to graze their cropland or access crop residues, in the belief that the compaction from their hooves will reduce subsequent crop yields. Multiple research trials, however, have been conducted at the University of Nebraska to study this impact, in multiple situations (no-till, conventional till, sandy soil, clay soil, continuous corn, corn–soybean, fall grazing only, grazing until spring, etc.). These studies have concluded that in most cases the presence of cattle made no difference in yield of subsequent crops, a few showed a slight yield decrease, and about the same amount showed a slight yield increase.

Bottom line: You might as well graze that residue and turn it into beef, as long as you do not bare the soil.

Benefits of Ruminant Livestock

Removal of large herbivores from cropped areas in hindsight has been a mistake. While unmanaged livestock can indeed be destructive to soil conservation, properly managed ruminant livestock (as described in Chapter 11) can be just as beneficial. Following are some of the primary benefits of integrating ruminant livestock into a cropping system.

HUMUS GENERATION AND NUTRIENT CYCLING

The soil is a microbial fermentation vat; the rumen is a microbial fermentation vat. The processes that take place in

the rumen are analogous to those that will take place eventually in the soil, only they proceed faster and more efficiently in the rumen. Most crop residues are very low in protein, and their decay on the soil surface typically contributes little to humus production. Also, most often the soil surface is only intermittently moist.

On most cropped fields, there is often a small amount of green vegetative (i.e., high-protein) plant matter in the form of grassed waterways, grassed field access roads, or cover crops. This green matter may be several hundred yards or as close as a few inches away from crop residue, but it doesn't matter; to a microbe, even a few inches away is the same as the distance between Earth and Mars to us. A microbe cannot travel even a few inches across dry, UV-radiated surfaces to get the protein from that green matter to combine with the low-protein crop residue.

A cow can gather high-protein materials from one area and low-protein materials from another, chew them into a relatively homogenous blend, put them into the rumen where there is no UV radiation and moisture is constant, inoculate them with microbes and let them ferment, then deposit the material into a perfect humus-building material in the form of a cowpie. Cowpies also are attractive to a host of other living creatures, such as dung beetles and earthworms, that can simultaneously incorporate the contained plant nutrients deeper and spread them across a wider area, increasing their effectiveness.

The data in the table, courtesy of the University of Nebraska, illustrate how grazing can boost soil microbiology, which in turn benefits soil structure and organic matter.

ECONOMIC RETURN

Ruminant livestock can provide economic return for soil conservation practices such as cover crops, grassed waterways, grassed terraces, grassed turnrows and field edges, grassed buffer strips, and the like. No matter how conservation-minded a farmer is, conservation takes a back seat to cash return when times get tough. The ability to convert conservation areas into dollars makes them much more likely to remain as conservation areas.

HOW GRAZING CORNSTALKS AFFECTS SOIL MICROBIOLOGY

TREATMENT	NO GRAZE	FALL GRAZE	SPRING GRAZE
nmol/g*			
Total FAME**	62.7	74.8	76.2
Bacteria	32.3	38.6	39.1
Actinomycete bacteria	3.32	4.32	4.21

*Nanomoles per gram of the identifying fatty acid **Fatty acid methol ester ***Arbuscular mycorrhizal fungi

SOURCE: H. Blanco-Canqui, M. K. Rakkar. R. A. Drijber, M. E. Drewnoski, J. C. MacDonald, and T. Klopfenstein, *Soil Science Society of America Journal* 81 (2017): 414-424.

HOW GRAZING CORNSTALKS AFFECTS SOIL MICROBIOLOGY

Micro–eukaryote	1.97	2.28	2.1
AMF* **	5.04	5.28	5.62
Saprophytic fungi	3.12	4.01	4.21

*Nanomoles per gram of the identifying fatty acid **Fatty acid methol ester ***Arbuscular mycorrhizal fungi

SOURCE: H. Blanco-Canqui, M. K. Rakkar. R. A. Drijber, M. E. Drewnoski, J. C. MacDonald, and T. Klopfenstein, *Soil Science Society of America Journal* 81 (2017): 414-424.

Utilizing Perennial Forages

Ruminant livestock can utilize perennial forages that are part of a crop rotation, such as alfalfa or perennial pasture mixtures. Honestly, is hay or pasture worth anything economically without ruminant livestock? The positive benefits of including a pasture phase in a crop rotation have been well documented for centuries. Some of the experiments at Rothamsted Research in the United Kingdom are the longest-running crop rotation research trials in the world, stretching back over 150 years. There are still detectable yield differences from plots that were in pasture a century ago.

Pasture is far more beneficial than hay, which removes much more biomass from the field and does not return manure to the system. The fastest route to increased organic

matter without importing it from another area is to plant a perennial blend of grasses, legumes, and forbs, and to cycle that material through a rumen to be deposited as manure on the soil surface. Whether a field in such vegetation is kept as pasture or rotated back into crops, the soil-building effect of that vegetation will persist indefinitely.

Recent research at the University of Florida demonstrates the beneficial effect of including a pasture for as short a period as two years in a crop rotation. When compared to a cotton-peanut rotation, a rotation of two years of bahaigrass, followed by a year of peanut and a year of cotton, had much higher peanut yields and dramatically higher profits. Much of this yield increase was attributed to a sharp decrease in parasitic nematodes. During the study period, the sod-based rotation had a near doubling of organic matter content.

Pasture is far more beneficial than hay, which removes much more biomass from the field and does not return manure to the system.

MORE FOOD FROM THE ACRE

A typical grain crop will produce roughly half of its biomass as grain, and the other half as crop residue. This crop residue consists primarily of cellulose, a polymer of glucose that all “higher” animals lack the ability to digest. Here’s the win-win method that they (we) have evolved to transform that indigestible material into nutrition.

Only microbes can digest cellulose.

Animals that have a microbial fermentation chamber allow the microbes into their gut to digest the cellulose.

The animals digest the microbes.

The humans eat the animals.

This is the only viable way to produce large amounts of food from intact grassland ecosystems.

The vast quantities of cellulose produced as a by-product of grain production is useless as a human foodstuff without the miracle of the rumen or cecum. The animal product from these acres can be considered a bonus crop to the grain. Additionally, a cover crop can ordinarily be inserted into a grain rotation, and this cover can be grazed for additional yield of animal product.

ELEPHANTS AND SNAILS—AND MICROBES

Yes, cattle do emit methane, a potent greenhouse gas, as do deer, rabbits, water buffalo, horses, termites, and humans who eat a lot of beans. Every foliage-eating herbivore on the planet emits methane. Elephants, for example, emit a huge amount of methane daily (according to one source, enough to propel a methane-powered car 20 miles a day).

But most people don't realize that many soils also emit methane, particularly soils that have standing water, such as rice paddies and wetlands. A rice paddy on average emits 16 times more methane per acre than an intensely stocked pasture full of cattle. Should we drain wetlands to combat climate change? Absolutely not—they are highly valuable natural ecosystems that perform vital planetary services, just as grasslands do.

It has also been discovered recently that most pasture soils contain a type of microbe that eats methane (called **methanotrophs**), so there is some natural mitigation of methane emissions on pastures. Since there are fewer ruminants on this planet now than at any time in recent history, why are fingers of blame for climate change now being pointed at one single species of ruminant?

Remember, the same processes that take place in the rumen also take place in the soil. Decay of plant residue in the soil produces both carbon dioxide and methane, just like plant residue being fermented in a rumen. The difference is that one process gives us burgers and butter; the other does not.

The Truth about Methane

It saddens me that so many people are reducing consumption of lamb, goat meat, and particularly beef, in the belief that it benefits the environment. This decision is highly counterproductive, since pastured livestock are perhaps the most environmentally friendly form of agriculture there is. The substitution of grain legumes for meat as the primary dietary protein source encourages the destruction of diverse ecosystems and their replacement with large blocks of monocultures.

Livestock production on biologically diverse pastures allows for wildlife protection and food production in the same acre. Also, pastures sequester soil carbon and

thereby can actually counteract rising global atmospheric carbon dioxide, while annual grain crops tend to deplete soil carbon.

The Bottom Line

The bottom line is that ruminant livestock are a natural and greatly beneficial cog in soil-building efforts. We need ruminant herbivores on this planet to maintain grasslands in a healthy state.

These natural sources of methane have been present for millions of years on this planet; they are not the cause of our recent problems. Methane levels are rising because of exploration for fossil fuels, period. When I was a kid, we had an oil well drilled on our land that unfortunately for us struck no oil. But it did hit natural gas. They let that well bleed out natural gas, and it whistled for years. I imagine that single well emitted more methane than all the cattle we raised in my lifetime, and probably more than all the bison that wandered the land before my family ever set foot on it.

The bottom line is that ruminant livestock are a natural and greatly beneficial cog in soil-building efforts. We need ruminant herbivores on this planet to maintain grasslands in a healthy state.

BUT DO WE HAVE TO EAT THEM?

I know many people who are hesitant to eat meat because they do not wish to eat other sentient beings, and I can understand that. Some of these people acknowledge that ruminant animals are critical to maintaining grassland ecosystems and understand that we need them. But they also ask, can we just let them be and not kill them? The answer is no.

Let us take a cow, for example. A typical cow will live to 10 years of age. In this time frame she will naturally give birth to 7 to 8 calves. Within 10 years, not only will she have 8 calves, but some of those calves will have calves, and some of *their* calves will have calves. If you know how to work the math on population dynamics, that single cow will end up with a *lot* of descendants (by my best estimate, 54) in just 10 years.

Not many environments can sustain a 50-plus-fold increase in animal numbers. While we don't have to eat them, we do have to kill them. That is reality. If we do not kill part of them, they would quite literally destroy the ecosystem and all the other life that depend on that ecosystem.

It is our responsibility to keep the ecosystem healthy by balancing animal numbers with carrying capacity. Some people might say, just let nature take its course and let the animals die a natural death. Nothing would be more cruel. A mature, ruminant animal at the end of its life eventually becomes so progressively weak that she cannot move enough in a day to gather sufficient food energy to meet her needs. She becomes emaciated and eventually becomes so weak she cannot walk to water and dies of thirst.

I have witnessed this, and it is an awful, gut-wrenching sight. It is far more humane to harvest an animal in a quick and painless method, and it makes complete sense to make use of that animal's embodied biological energy to sustain other life-forms on Earth, with my fellow humans being a priority on my personal list to get first shot at that energy over vultures and maggots.

Testing for Soil Organic Matter

It is often said you cannot manage what you cannot measure. It is extremely helpful to have some sort of measuring stick to help you track progress in your soil-building efforts over time. One simple measure is soil organic matter, but changes in soil organic matter are often very, very slow, and slight variations in sampling can lead to large variations in test results. Earlier in this chapter I stated that increases in soil microbial biomass are probably the single best way to measure your soil restoration efforts. One test to measure microbial biomass in the soil is a test called the PLFA (Phospholipid Fatty Acid Analysis) that is now being offered by a few soil-testing labs across the country.

This test essentially extracts all the phospholipids in the soil. Since phospholipids are found only in living organisms as part of their cellular membrane, this test can measure the total living biomass in a soil. It can also determine a rough estimate of the biomass of different categories of organisms, such as

bacteria, fungi, and protozoans by differences in the phospholipids found among all these organisms.

Currently, this is the single best commercially available soil test for measuring your soil quality. Use it as a benchmark when you are beginning this journey, and take new samples over time to gauge your progress. The table below interprets the numbers of a PLFA test and classifies them into soil quality rating.

EAT YOUR SHORTS

The PLFA test is useful because it gives us a number. But for a very nice visual demonstration of microbial activity in one field compared to another, try the "I Soiled My Undies" test.

Simply buy a few pair of "tighty whitey" cotton underwear, and tie a flag to the waistbands so you can find them later. Now bury them in different soil situations for comparison, such as no-till versus tilled, cover-cropped versus no cover crop, pasture or forest versus cropland. (See Figure 3.4.)

The higher the level of soil microbial activity, the faster the underwear will decompose. A good soil will eat up all but the elastic waistband in one month.

MEASURING MICROBIAL BIOMASS (PLFA TEST)

TOTAL BIOMASS (in nanograms per gram of soil)	DIVERSITY	RATING

MEASURING MICROBIAL BIOMASS (PLFA TEST)

< 500	< 1.0	Very poor
500 to 1000	1.0+–1.1	Poor
1000 to 1500	1.1+–1.2	Slightly below average
1500 to 2500	1.2+–1.3	Average
2500 to 3000	1.3+–1.4	Slightly above average
3000 to 3500	1.4+–1.5	Good
3500 to 4000	1.5+–1.6	Very good
>4000	>1.6	Excellent

CHAPTER 5 SUMMARY

- The biological activity of soil is often a very good measure of soil quality, as the conditions that promote plant growth will also promote soil microbes, fungi, and animals. Conversely, soil biology also creates conditions that promote plant growth.
- Earthworms are one of the most beneficial soil organisms. In their tunneling and excavation they open up abundant pore space for soil oxygenation and rainfall infiltration.
- Dung beetles also promote soil pore space through tunneling activity. In addition, they incorporate the dung of pastured livestock into the root zone of pasture plants, which is highly beneficial to pasture ecosystems. Their populations have been decimated in recent decades by overuse of systemic insecticides intended to control livestock insect and nematode pests.
- Soil microbes drive almost all desirable soil reactions. Although some soil microbes are pathogens (cause disease of plants), most are beneficial. In general, populations of microbes can be increased by keeping the soil covered and by feeding them. The primary source of food for soil microbes is root exudates, secondarily plant residues, and thirdly animal remains and animal manure.

- Soil microbial populations can be promoted by:
  - elimination of tillage
  - maintaining a cover of crop residue or live plant leaves at all times
  - maintaining living roots in the soil
  - adding additional organic materials to the soil surface such as animal manure or compost.
- Some commercial microbial inoculants have value, others less so. Using scientific methods to test inoculants can help sort out useful products from ones that are not.
- Mycorrhizal fungi are a particularly useful class of organism that help plants extract water and nutrients from the soil and exude glomalin, which is a powerful soil aggregating agent. They are particularly rare in cropland soils with a history of fallow, which starved them out, as mycorrhizal fungi require live roots for a host.
- Microbes perform best when their food source has a balance of carbon and nitrogen, which are necessary for forming protein. If the food is too low in nitrogen, then microbial decay depletes soil nitrogen and can result in nitrogen deficiency of crops. If nitrogen content is high, the decay of the residue can act like a nitrogen fertilizer. If nitrogen is either too high or too low, then less organic matter is produced than if the carbon and nitrogen are in a ratio of 20 to 30 carbons per each nitrogen.
- The processes that take place in a ruminant animal digestive tract are similar to what takes place within the soil to

produce organic matter, only they happen much faster and more efficiently. Ruminant manure is a powerful soil improvement medium and contributes more to soil organic matter and soil microbes than the decay of the plant materials that were eaten by the animal to produce the manure.

- There are testing methods that measure microbial populations. A laboratory test is called the PLFA; a very informal, subjective, and fun test anyone can conduct with cheap and easily available materials is called the “I Soiled My Undies” test!

06

Minerals

In the typical cropped soil, lack of mineral nutrients is often a severely limiting factor to plant growth, so we have applied fertilizers to supply them.

Originally these fertilizers were organic in nature, such as animal manure or by-products of agricultural processing such as cottonseed meal or meat and bone meal. Then, as the specific minerals necessary for plant growth were discovered, the mining and manufacture of fertilizer materials specific for those plant nutrients began.

There is, however, only so much of these materials on the planet, and someday we will run out; how will we grow crops in the future without the synthetic fertilizers on which we have become dependent? Perhaps the answer lies in the harnessing of the biological processes that created our original storehouse of available soil fertility in natural ecosystems.

Achieving an active soil biology, however, depends primarily on maximizing plant biomass, and this requires a supply of essential mineral nutrients. Additionally, the pH of the soil needs to be in a relatively neutral range.

Plant Mineral Nutrients

From the soil, plants require nitrogen, phosphorus, potassium, sulfur, calcium, iron, magnesium, copper, zinc, molybdenum, boron, chlorine, manganese, silicon, and nickel. Undoubtedly, we will also discover that many other elements are necessary for plant growth or need to be present in plants for animal nutrition.

How Nutrients Move within Soil

Plant nutrients move to roots primarily through two mechanisms: mass flow and diffusion. **Mass flow** is the movement of nutrients (dissolved in the soil solution) into the plant with water uptake. This mechanism is relatively fast, and nutrients that are taken up by this method can move relatively long distances (several inches!) in the soil. Nutrients that move into plants primarily by mass flow include nitrogen, sulfur, boron, and chlorine; these nutrients exist in soil in highly soluble forms.

With the other method of uptake, **diffusion**, nutrients are bound tightly to the surface of soil particles by electromagnetic charges. Locations that have an electric charge are called exchange sites. The nutrients jump from exchange site to exchange site as the sites closest to the roots are vacated upon nutrient uptake. Not surprisingly, this is a very slow process, and it is limited in some cases to less than an inch of movement in a growing season.

Obviously, location of nutrients within the root zone is an advantage for successful uptake of these nutrients. Enter mycorrhizal fungi, the symbiotic organisms that colonize plant roots. Part of the fungus lives inside plant roots, and the rest of it forms threadlike hyphae that reach up to 18 inches away from the root, greatly increasing the amount of soil a root system explores. The amount of otherwise immobile-in-the-soil nutrients that can be accessed by a plant increases severalfold when the plant root system is colonized by mycorrhizal fungi.

How Minerals Move within Plants

Just as the mobility of different minerals in the soil varies, it also varies within plants. Some nutrients readily move throughout plants, while others are put into structural components of the plant and do not move once incorporated into plant tissue. Potassium, for example, is not part of many plant molecules. It functions much like sodium in an animal body in regulating water balance and therefore readily moves throughout the plant. Calcium, by contrast, is a component of

cell walls and cannot be moved within the plant without serious consequences.

Plants ordinarily move what nutrients they can from older plant tissue to new plant tissue during plant growth. Therefore, if a nutrient is mobile within a plant, a deficiency will show up first in the older tissues of a plant. If a nutrient is immobile, deficiency will show up first in the younger growth of a plant. Nutrients that are mobile in plants include nitrogen, phosphorus, potassium, magnesium, molybdenum, and chloride; if deficient, these nutrients will become deficient first in older leaves. All other nutrients, including calcium, sulfur, iron, copper, zinc, boron, and manganese, are immobile; these become deficient first in young leaves and newer growth.

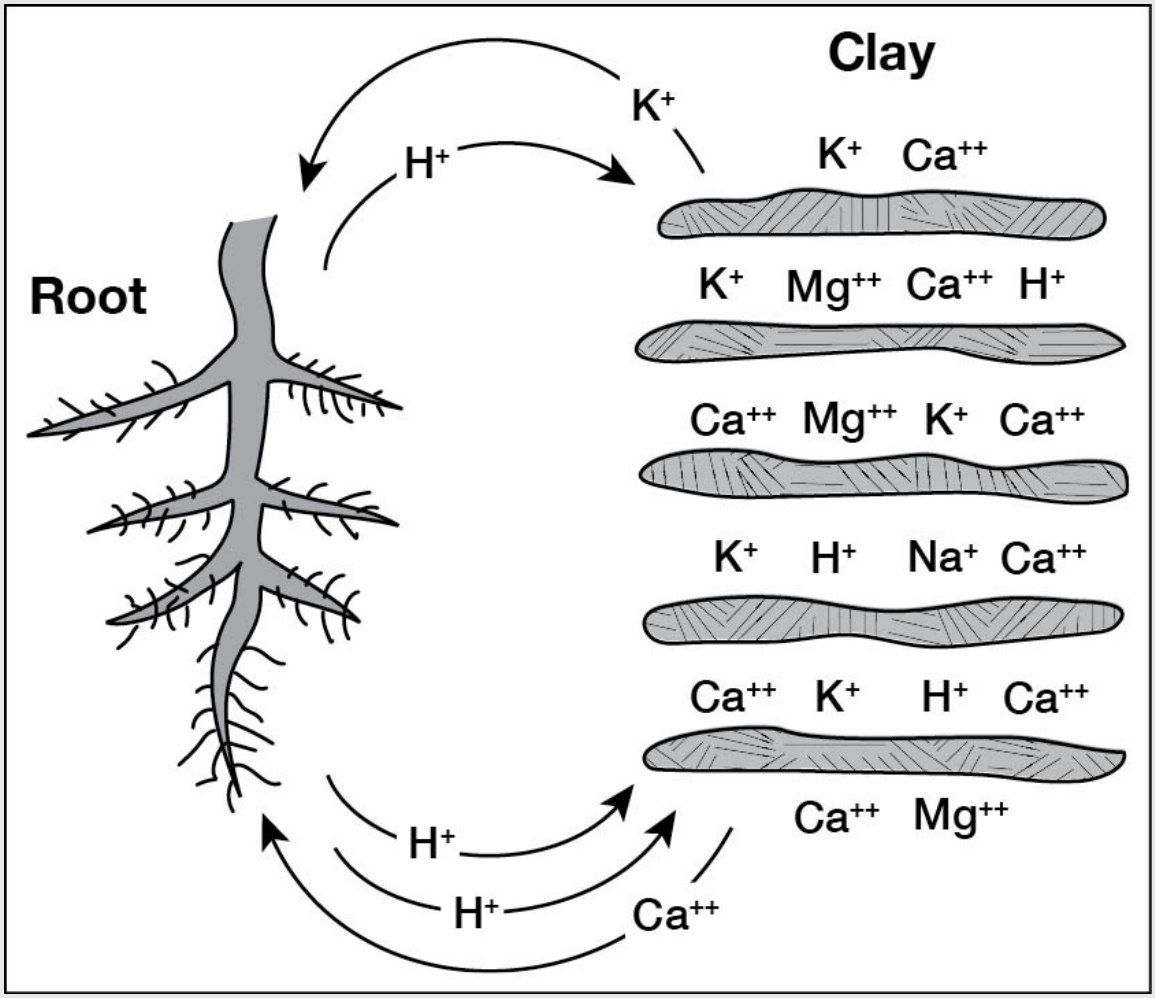
Cation Exchange Capacity

Nutrients that move into the plant rapidly, through mass flow, could be described as being mobile within the soil. Plant nutrients are primarily (but not always, as we will eventually see) taken up as **ions**, which are either positively charged (called **cations**) or negatively charged (called **anions**). Soil particles have a predominantly negatively charged surface, and since particles with opposite electric charges are attracted to each other, soil particles are highly attracted to cations and hold them tightly to their surfaces.

Think Positive

Cations (positively charged ions in the soil) are tightly held to soil particles (clay, sand, silt, or humus), which have a negative charge by magnetic attraction. For a plant to remove a plant nutrient with a positive charge from a soil particle, it must exchange a like amount of electrical charge with the soil particle.

Since plants generate hydrogen ions (H+) during photosynthesis, these can be used as a currency to keep both plants and soil particles electrically neutral. One H+ will exchange for a monovalent (single charge) cation, such as potassium (K+), and two H+ are needed to exchange for a divalent (two charge) cation, such as calcium (Ca++).



This ability of the soil to attract and hold cations is referred to as **cation exchange capacity**, or CEC. Not all soil particles are equal in CEC. Sand has very little surface area, very little charge, and very little CEC. Clay, as evidenced in the photo, Figure 2.2, has tremendous surface area per unit weight, and these surfaces tend to be highly charged. Thus, clay has a huge amount of CEC and a high capacity to hold both nutrients and

water. Water has a positively charged end to the molecule, and high-CEC soils hold water as well as cations.

Indiana Jones Weighs In

A plant must always replace the cation with another cation, similar to how Indiana Jones had to replace the gold idol with a bag of sand weighing exactly the same.

To obtain a cation from an exchange site for plant uptake, the plant must give off a hydrogen ion (H+) so that both the plant and the soil will remain electrically neutral. Cations therefore tend to be rather immobile within the soil. Nutrients that are taken up by plants in the form of cations include:

- Nitrogen (ammonium, NH4+)
- Potassium (K+)
- Calcium (Ca ++)
- Magnesium (Mg++)
- Iron (Fe++)
- Copper (Cu ++)
- Zinc (Zn ++)

Most of the anions will move freely within the soil with the movement of water and include:

- Nitrogen (nitrate NO_3^-)
- Sulfur (sulfate SO_4^{--})
- Boron (borate BO_4^{--})
- Chloride (Cl^-)

Phosphate, despite being an anion, is extremely immobile in the soil.

Standard soil tests can be useful in the early stages of a soil-building effort, but as an active amount of organic matter and soil biology is accumulated, new testing procedures become necessary.

Testing for Nutrient Needs

Nutrient needs should be assessed by soil testing, but soil testing is not an exact science. For example, if a soil test says that a soil has 20 parts per million (ppm) of phosphorus (equivalent to 40 pounds per acre), and a crop requires 50 pounds per acre, it would seem that you simply need to add another 10 pounds of phosphorus. But it doesn't work that way. That 20 ppm is an availability index, not an absolute amount, and the recommendation is nothing more than an educated guess. The recommendation also must take into account that a

fairly high percentage of applied phosphorus gets tied up before it ever gets into the plants.

THE HANEY TEST

Soil fertility recommendations have been developed over a lot of years of trial and error. The problem is, most of those years were when the typical farm was farmed with conventional tillage, no cover crops, and seldom any manure input. The standard tests are pretty accurate in conventional tilled fields with average to good yield levels. But with reduced tillage and the use of cover crops and recycling of organic materials such as manure back to the land, these standard tests may not be entirely useful. Standard soil tests can be useful in the early stages of a soil-building effort, but as an active amount of organic matter and soil biology is accumulated, new testing procedures become necessary.

Seeing this need, Dr. Rick Haney has developed a set of tests that more accurately reflect nutrient needs in biologically active soils. Request a Haney test the next time you soil-test; although expensive, it gives much more useful information if you have a biologically active soil. Even if you do not, this test gives you a baseline with which to compare future soil tests. People who really understand soil testing are fond of saying, “All soil tests are inaccurate, but some are useful.”

FERTILIZER ANALYSIS

To find out how much value is in a material we use a fertilizer analysis. The standard analysis in the United States presents

three numbers separated by dashes, and those three numbers represent, in order, the percent of:

- Nitrogen (N);
- Phosphorus pentoxide (P_2O_5, but often commonly referred to as phosphate); and
- Potash (K_2O).

For example, a fertilizer with an analysis of 9-24-6 contains 9 percent nitrogen, 24 percent phosphate, and 6 percent potash.

Any micronutrients usually appear after the standard analysis and are followed by the chemical symbol for that element. For example, ammonium sulfate would be 21-0-0-24S, meaning it contains 21 percent nitrogen, no phosphate or potash, and 24 percent sulfur.

Soil pH

Soil pH is a measure of the acidity of a soil. Acidity is a term for the concentration of hydrogen ions. The term **pH** refers to the negative logarithm of concentration of hydrogen ions in solution. Thus, a water solution with a dissolved concentration of 0.01 (or 10^{-2}) will have a pH of 2, while a solution with a concentration of 0.001 (or 10^{-3}) will have a pH of 3.

You can also see that the first solution with a pH of 2 has ten times the hydrogen ion of the second solution. Thus, the pH scale is logarithmic: Each point move on the pH scale indicates

a tenfold change in acidity. A soil with pH 6 is ten times as acidic as one with pH 7; a soil with pH 5 is a hundred times more acidic than one with pH 7; and a soil with pH 4 is a thousand times more acidic than one with pH 7.

The pH scale runs from 0 to 14, with 0 being the most acidic and 14 being the least acidic. A pH of 7 is considered neutral. Anything with a pH higher than 7 is referred to as basic or alkaline. Almost all life forms require their environment and their bodies to be somewhat close to neutral to survive, though there is some variation in this. Many soils used for agriculture have a pH that is not desirable for optimum growth of the desired crops.

Why Soil Becomes Acidic

Soils in humid areas (where annual rainfall is in excess of annual evapotranspiration) usually tend to become more acidic over time, then stabilize at a moderately acidic level. This is because rainfall is naturally acidic. Dissolved carbon dioxide in rainfall lowers the pH of natural rainfall down to 5.5, which is lower than most agronomic plants prefer. Although the amount of natural acidity in any one rain or season is very small, centuries of rain add up over time.

Acid rain is another cause of soil acidity. Before there was as much concern about air quality as there is now, coal-burning power plants and diesel fuel poured thousands of tons of sulfur dioxide into the atmosphere. Sulfur dioxide combined with water forms sulfuric acid. This made rainfall abnormally

acidic, as much as pH 4 in some places downwind of power plants or urban centers. (There are recorded cases of rainfall being measured as acidic as pH 2!)

This level of acidity is toxic to almost all living organisms. That is why pickled foods have such a long shelf life—because microbes cannot exist in such acidic environments.

Now that the air is getting cleaned up through low-sulfur diesel and scrubbers installed at power plants, acid rain is happily becoming less of an issue, but the legacy of it still affects many areas. The issue of acid rain is one of the few environmental calamity stories with a fortunately happy ending.

Acid Test for Rainfall

In areas in which rainfall is less than evapotranspiration, you can often tell from a soil pit what the approximate annual rainfall is. The surface soil may be acidic, but the subsoil is most often alkaline because the soil moisture tends to evaporate faster than it can move down in the soil.

To determine how deep into the soil rainfall tends to penetrate on average, dig a soil pit, climb inside and squirt drops of a powerful acid on the wall of the soil pit and when you hit the line where the subsoil becomes alkaline, the soil will bubble and fizz where the acid hits it. The depth from the surface to this layer is almost always equal

to the annual rainfall. For example, in a 25-inch rainfall area, this depth will usually be at 25 inches.

Nitrogen and sulfur fertilizers can also increase soil acidity when acted on by microbes. Ammonium-based fertilizers create hydrogen ions (acidity) when bacteria convert them into nitrate. Each pound of nitrogen fertilizer creates enough acid that it requires 2 pounds of pure agricultural lime to neutralize it. Sulfur in elemental form also is oxidized by bacteria and creates considerable acidity; each pound of elemental sulfur requires approximately 4 pounds of ag lime to neutralize it.

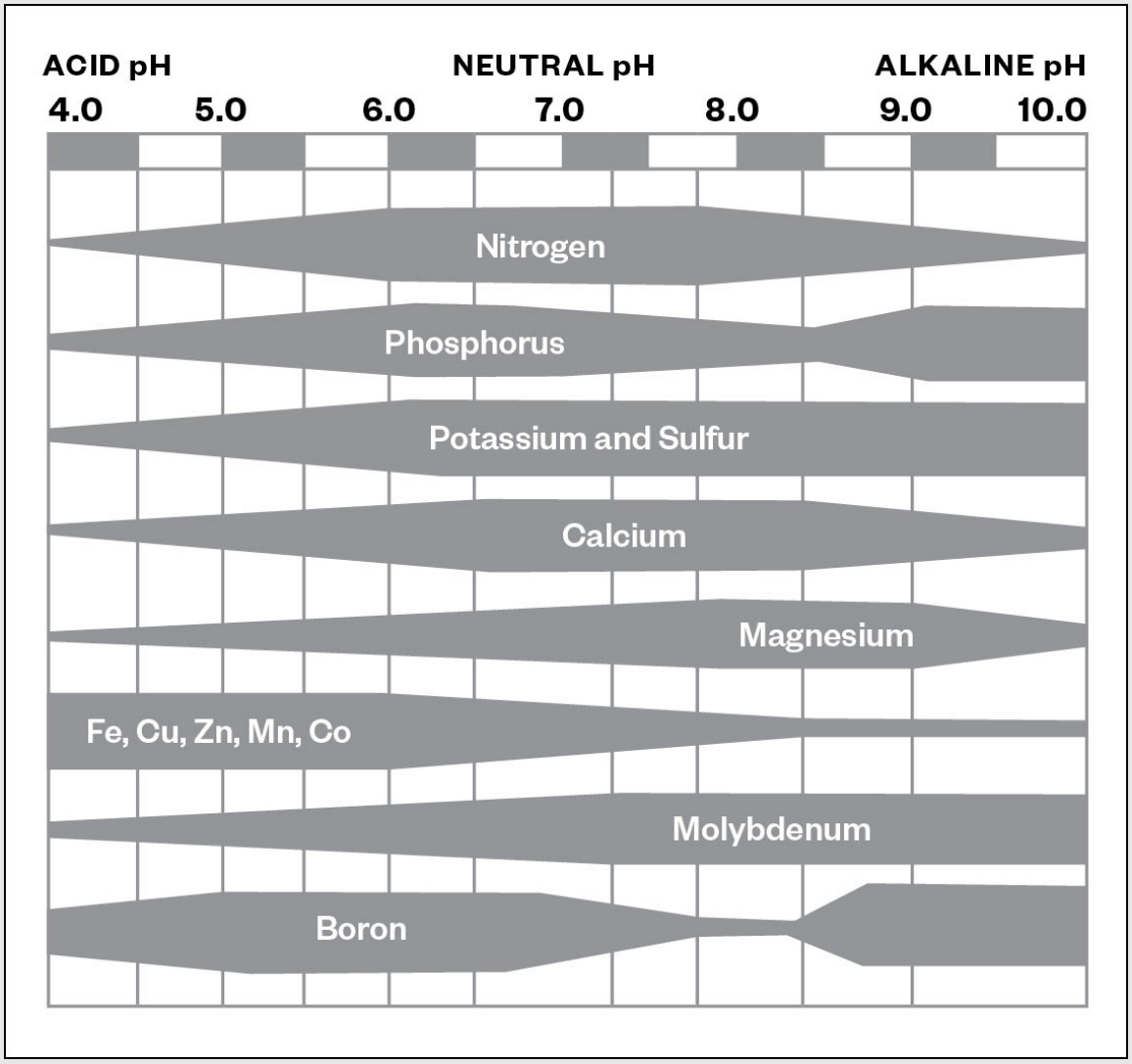
Geologic parent material in some soils can create acidity or prevent acidity. Limestone-derived soils tend to neutralize acidity, but this neutralization effect decreases with soil depth, when the subsoil is far enough from the surface, so that even soils with limestone parent material can become acidic. On soils with similar rainfall, soils derived from granite or shale will be more acidic than limestone-derived soils. Soils with pyrite minerals (sulfides of iron or other metals) can oxidize and become very acidic. This commonly happens on many spoil piles from metal mines, such as iron mines.

How Too Much Acid Affects Soil

Excess acid can have a number of detrimental effects on soil, including:

- Low uptake of Ca, Mg, P, and Mo. This can negatively affect plant growth or growth of animals eating the plant material.
- Increased levels of Al, Mn, and Fe. Free aluminum is highly toxic to plant roots, and although Fe and Mn are plant nutrients, their availability in acidic soils can sometimes reach toxic levels or interfere with uptake of other micronutrients. All three can render phosphorus unavailable at low pH.
- Poor bacterial growth. This includes the bacteria that cause nodulation and nitrogen fixation on legumes. The failure of many legume seedings in pastures can be traced to a layer of surface soil acidity that is a result of many years of nitrogen fertilizer being broadcast on the soil surface.
- Poor soil structure. This can occur in acid soils, largely as a result of inadequate calcium. Calcium has a very beneficial effect on soil aggregation and structure. Liming can often make a soil looser and more friable.

How Soil pH Affects Nutrient Availability



Redrawn from: Truog E (1946) Soil reaction influence on availability of plant nutrients. Soil Science Society of America Proceedings 11, 305-308

How to Remedy Soils That Are Too Acidic

The term pH refers to the amount of hydrogen ions (H+) in the soil solution. This is called **active acidity**, and though this is the form of acidity that causes plant response, it is an incredibly low percentage of total acidity in the soil. The total amount of H+ ions in the solution of even a very acid soil could be completely neutralized by just a few pounds of finely ground limestone rock. But that is not all the acidity present in an acidic soil. In fact, it may be just one-tenth of one percent of the total acidity in a soil.

The majority of the soil acidity actually consists of hydrogen ions attached to soil colloids (clay and humus) and in other minerals, not out floating in the soil solution. This form of acidity, known as **reserve acidity**, is normally a thousand times or so greater than the hydrogen ions in solution.

So why do we even bother measuring pH (active acidity) when it is so small a percentage of the total acidity? It is because the number of ions in solution and the number of ions in reserve always seek to reach an equilibrium. For example, if you neutralize the hydrogen ions in solution with an alkaline material, such as limestone, more come off the colloids to replace them.

It is like zombies in *The Walking Dead*. You kill all the ones in front of you, and more appear out of nowhere to replace them. If you add acid to the soil, most of the hydrogen ions will be pulled out of solution by the colloids and become part of the reserve acidity.

PH AND LIME

Solution pH indicates whether or not you have a problem, and how much the problem will affect plant growth, but it does not tell you how much liming material you need to neutralize the problem because it does not measure the reserve acidity. The reserve acidity is largely dependent on the cation exchange capacity (CEC) of the soil, which is a measure of how many sites there are on the sum of the exposed soil particle surfaces capable of having a cation (positively charged ion).

The soil particles that have very high amounts of CEC are clay and humus. Soils with a high amount of clay and humus are capable of holding far more acidity (as well as water and nutrients) than a sandy soil low in humus. A sandy soil with pH 5 might require 1 ton per acre of lime, while a clay soil high in organic matter at pH 5 might require 4 tons per acre.

LIMING MATERIALS AND ECC

ECC (effective calcium carbonate) is a measure of the neutralizing power of a liming material. It is based on a number of factors, including the chemical composition, the fineness (particle size) of the material, and the purity of the material. The most common liming material is finely ground limestone (calcium and magnesium carbonate) rock.

A material with 100 ECC has the neutralizing power of 100 percent pure calcium carbonate and is composed entirely of particles that will pass through a 40-mesh screen (a screen with 40 wires per inch in both directions), which is basically the same fineness as commercial wheat flour. Most commercially available agriculture-grade lime is nowhere

close to 100 ECC because it is neither fine enough to pass through a screen this small, nor is it pure calcium carbonate; it usually contains some shale or quartz sand or iron oxides or some other rock material.

Determining Proper Amount of Lime

Soil tests have a different measure from simple pH to gauge how much lime you need to bring a soil to a desired pH, and that is the **buffer pH**. To determine lime requirements, subtract the buffer pH stated on the soil from your desired soil pH, and then multiply by 900. This will give you pounds of ECC per acre needed to bring your soil up to your desired pH.

To determine the actual amount of liming material needed, start with the pounds of ECC required per acre (from soil test results) and divide by the percent of ECC converted to a decimal. For example, if the soil test calls for 4,000 pounds of ECC, and your lime source is 80 percent ECC, the actual lime material required is 4,000 divided by 0.80 = 5,000 pounds of lime material.

When Soil Is Too Alkaline

Although many soils around the world are undesirably acidic, other soils are undesirably alkaline in reaction, especially in drier climates. Alkalinity is almost always caused by either too much sodium or too much calcium carbonate. How to deal with excess sodium has already been discussed in Chapter 4. Excess calcium carbonate causes problems almost exclusively due to

its dramatic reduction of the availability of Fe, Mn, Cu, Zn, and P.

One way to remedy these problems is through acidifying the soil by adding elemental sulfur, but this is normally prohibitively expensive, and it creates other problems. Acidifying only a narrow strip of soil close to the crop row with sulfur can often alleviate these nutrient deficiencies temporarily. But a more economical strategy is to deal directly with the nutrient deficiencies themselves, as discussed later in this chapter.

The Essential Nutrients for Plant Growth

Currently, there are 17 chemical elements found to be essential for plant growth. Of these, three (carbon, hydrogen, and oxygen) come from air or water. The other 14 come from soil: nitrogen, phosphorus, potassium, calcium, magnesium, iron, copper, zinc, molybdenum, boron, chlorine, and manganese. Additional elements that may be required by some plants are nickel, silicon, and vanadium.

Nitrogen (N)

In most agricultural fields, as well as most natural ecosystems, the plant nutrient that is most often deficient (or **limiting**) for optimal productivity is nitrogen, taken up by plants as either

ammonium (NH_4+) or nitrate (NO_3-). This is curious, since Earth's atmosphere is 78 percent N, but atmospheric nitrogen is in the form of N_2, a triple-bonded molecule that is the strongest molecular bond in nature. It takes an enormous amount of energy to break this bond (luckily for life on Earth, it is also broken by an enzyme found in certain bacteria, blue-green algae, and actinomycetes).

The Haber-Bosch process is a method of industrially converting methane (natural gas) and atmospheric nitrogen (N_2) into anhydrous ammonia (NH_3), which forms plant-available ammonium when combined with water. This is the basis for almost all nitrogen fertilizer in current use worldwide. Synthetic forms of nitrogen include not just anhydrous ammonia (82-0-0), but also urea (46-0-0), ammonium nitrate (34-0-0), ammonium sulfate (21-0-024), and urea-ammonium nitrate solution (28-0-0 or 32-0-0). There are also many blended nitrogen fertilizers that contain varying amounts of nitrogen.

UREA AND ANHYDROUS AMMONIA

Anhydrous ammonia is a liquid when held under pressure but becomes a gas when the pressure is released. It must be injected underground to prevent it from escaping into the atmosphere. It is almost always the cheapest nitrogen fertilizer material but is hazardous to apply and requires specialized equipment for application. Many feel anhydrous ammonia is toxic to soil organisms, and during application there is a zone immediately around the injection site and about 3 inches in radius where microbes are killed.

I was taught that the microbial population rebounds to normal levels within three weeks of application, but the question remains: Which microbes rebound? Many people have told me that their soil structure improved after moving away from anhydrous ammonia. Perhaps, as with so many other toxins, the dose makes the poison.

Although it is the most common dry granular fertilizer, urea is subject to volatilization losses when surface-applied to residue-covered fields. This is because many crop residues contain urease, an enzyme that breaks urea into carbon dioxide and ammonia gas. Urea should be applied prior to a rain for best use.

Although it is a naturally occurring compound, urea is synthetically produced commercially.

AMMONIUM NITRATE

Unlike urea, ammonium nitrate is not subject to loss through volatilization, which makes it a highly useful fertilizer for surface application. It is hard to obtain, however, because it can be combined with diesel fuel to manufacture an explosive mixture and is now highly regulated.

All synthetic nitrogen sources, whether they contain ammonia, ammonium, urea, or nitrate itself, are rapidly converted into nitrate by soil bacteria when soil temperatures are warm. This has both benefits and problems. Nitrate is highly mobile in soil because it has a negative ionic charge and is not magnetically attracted to soil particles, which also have a negative ionic charge.

Remember, when it comes to electrical charges, opposites attract. This means nitrate can move easily with water through soil toward plant roots. On the other hand, it can just as easily be lost during wet conditions when it leaches through the soil profile below the reach of plant roots.

Nitrate can also be lost when the soil is wet and there is no oxygen in the soil. In that case bacteria can strip the oxygen out of the nitrate molecule and convert it into either nitrous oxide (NO_2) or dinitrogen gas (N_2) which escapes into the atmosphere.

All synthetic nitrogen sources, whether they contain ammonia, ammonium, urea, or nitrate, are rapidly converted into nitrate by soil bacteria when soil temperatures are warm. This has both benefits and problems.

LEGUMES

Another way to obtain nitrogen in an agricultural setting is by using legumes as crops or in rotation with legumes utilized as forage. Legumes host *Rhizobium* bacteria in nodules on the roots that convert atmospheric nitrogen into plant-available nitrogen. Soybeans, alfalfa, clovers, and peas are all examples of legumes.

Utilizing legumes for a nitrogen source offers many advantages, but also some disadvantages. The major advantage, of course, is that the nitrogen produced is “free,”

although the planting of the legume can sometimes be rather pricey. If, however, the legume plant is used in some manner as a crop-particularly for grazing, in which case much of the nitrogen gets cycled back onto the land as manure and urine—then whatever nitrogen is contributed to the system is a by-product of the legume crop.

Legume nitrogen is in the form of protein, which is a slow-release nitrogen source that is not prone to leaching or denitrification, as most synthetic fertilizer forms are. However, the amount of nitrogen contribution from a legume crop is hard to measure and can be quite variable, ranging from zero to several hundred pounds per acre in some cases. Legumes also utilize all existing nitrogen in the soil before fixing any of their own. It is said that applying nitrogen makes legumes lazy and delays **nodulation** (development of root nodules).

In general, legume biomass is about 3 percent nitrogen, so each ton of aboveground biomass will contain about 60 pounds of nitrogen. This is not all plant-available nitrogen, however. As with any carbon-based fertilizer, the microbes sit at the table first and plants get the table scraps.

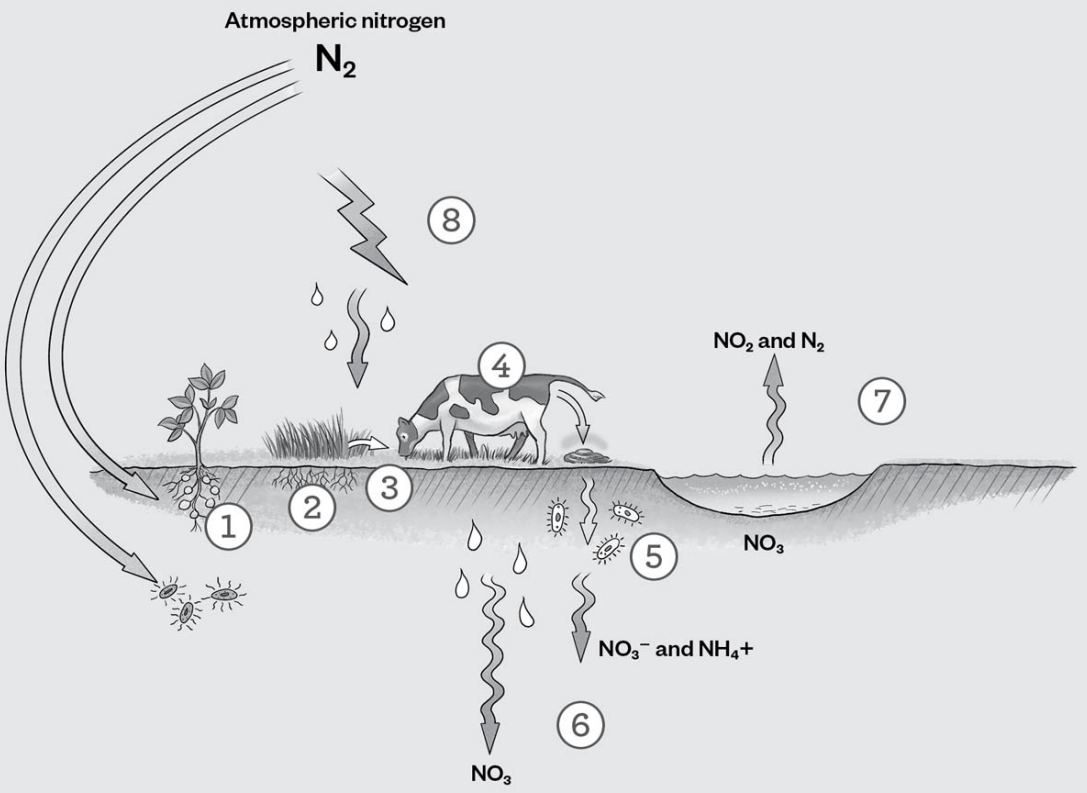
Microbes require about 30 pounds of nitrogen per ton of biomass for their reproductive needs, or about half the total. That means about 30 pounds per ton of legume residue will be left over for the plants. The half utilized by the microbes is not lost forever, since the microbes are eaten by other soil organisms in the future, and on average about half of the remaining nitrogen is released in each subsequent year.

For example, if a ton of legume residue is decayed in this year, there will be 60 pounds of total nitrogen, of which 30

pounds will be available to this year's crop, 15 pounds available to the following year's crop, and about 7.5 pounds available to the crop the year after that. If cover crops are used on a frequent basis, the slow release amounts of several years of previous cover crops combined can provide a very beneficial amount of total nitrogen. This is why the benefit of a program of cover crops and carbon-based nutrient applications will seem to increase over time.

It is also important to realize that the release of nitrogen from legume residue requires conditions conducive to microbial activity; in other words, warm, moist soil. This is why warm-season crops such as corn respond better to legume residue than cool-season crops such as wheat.

NITROGEN CYCLE

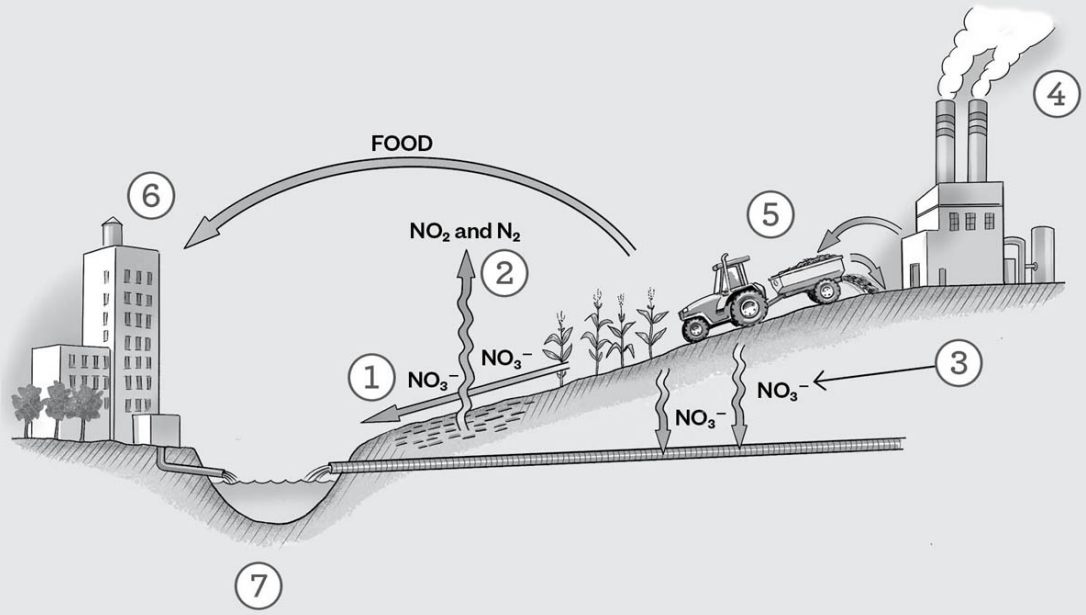


ABOVE:

1. Free-living nitrogen-fixing microbes in soil
2. Symbiotic nitrogen-fixing microbes on plant roots such as legumes
3. Nitrogen is taken up by plants and converted into protein.
4. Protein is ingested by animals and excreted in feces and urine.
5. Bacteria convert feces into NO_3– and NH_4+.
6. Excess water moves nitrate into groundwater. (The amount is small due to low levels of nitrogen in

nitrate form.)

7. Anaerobic soil causes denitrification and loss of nitrogen to atmosphere as NO_2 or N_2.
8. Lightning combines N_2, oxygen, and water into nitric acid, which falls in rain.



ABOVE:

1. High amounts of nitrogen are on surface soil from fertilizer application, leading to high amounts of nitrogen runoff into surface water.
2. High amounts of nitrate in soil lead to high amounts of loss from denitrification under anaerobic conditions.
3. High amounts of nitrate lead to high amounts of leaching when excess soil moisture moves into groundwater.
4. Atmospheric N2 is combined with CH4 (methane) in fertilizer manufacture to form ammonia.
5. Fertilizer is applied to fields and taken up by crops.

6. Nitrogen in the form of protein in food is shipped to cities.
7. Water-based sewage systems move nitrogen into rivers.

FREE-LIVING RHIZOSPHERE ORGANISMS

Another way to obtain nitrogen for agriculture is to use free-living rhizosphere organisms. There are actually dozens of species of nitrogen-fixing microbes in the soil, in addition to those that inhabit legume roots.

One example is *Nostoc*, a blue-green algae that inhabits the soil surface of prairies. *Nostoc* becomes quite abundant after a prairie burn due to the sudden influx of phosphorus and calcium from the ashes. It helps restore nitrogen volatilized from the plant material during the burn. Other species of nitrogen-fixing microbes live on the water plant *Azolla*, which lives in rice paddies.

Examples of bacteria that are known to fix nitrogen in the rhizosphere of many crop and forage plants are *Azospirillum* and *Azotobacter*. These two organisms are able to fix useful amounts of N in the rhizosphere of a large number of plants, including corn and sorghum. However, they are not often used in the agriculture systems of the more developed world for a couple of reasons.

First, the amount of N fixed is usually not enough to allow it to act as the sole nitrogen source for an economic yield; it's

typically only 20 to 30 pounds of N per acre. Second, if there is additional nitrogen added to the system, these bacteria will not fix any additional nitrogen. The reason for this seems to be that when plants are receiving high levels of nitrogen in the form of nitrate, they no longer produce the vital root exudates that feed the bacteria or the chemical signaling compounds that trigger the bacteria to populate the rhizosphere.

Putting Bacteria to Work

In the average American cornfield, soaked with anhydrous ammonia, these organisms have no value at all. But in an agroecosystem in which nitrogen is provided from slowly decaying protein from manure and legume residue, there is seldom enough available nitrate at any given time to suppress the fixation ability of free-living N fixers. Since legumes in rotation seldom provide enough nitrogen for maximum corn yield under optimal conditions, this could be an important asset.

Another potential niche for these organisms is as an inoculant for grass-legume mixtures, either as annual cover crop mixtures or perennial grass-legume pastures—because these mixtures seldom receive added nitrogen fertility and because the grasses in these mixtures are often somewhat nitrogen deficient. Inoculating with *Azospirillum* and *Azotobacter* would make all the plants in the mixture capable of fixing nitrogen, not just the legumes.

Carbon-Based: The Future?

If they can be obtained at reasonable cost, carbon-based fertilizer materials are perfect nutrient sources, and not only because they contain nitrogen. They also contain most, if not all, nutrients required by plants (because they come from plants), in most cases; and they have biological energy to stimulate microbial growth.

On a planetary basis, we *must* close the "poop loop" and return sewage back to the land, rather than allow these materials to escape to the ocean where we not only lose their fertility value from the land, but also where they cause pollution problems such as the hypoxic zone in the Gulf of Mexico. Carbon-based fertilizers are discussed later in this chapter.

OTHER SOURCES OF N

Additional sources of nitrogen (as well as many other nutrients) are residues of plant or animal materials, such as compost or manure. These are very useful fertilizers if they are readily available and transportation costs do not exceed their value. On a large scale, however, it is important to realize that these materials are means of recycling fertility, not creating it. They transfer fertility from one location to another.

For example, manure from a Kansas feedlot may have been created from corn grown in Iowa. The land around the feedlot is enriched at the expense of the field in Iowa, which must import a source of fertility from somewhere in order to maintain its supply.

The point here is not to say that utilizing these materials as fertilizer is a bad idea, far from it. It needs to be used somewhere, and it might as well be on your farm. It is just unrealistic to assume that 100 percent of the planet's fertility needs can come from recycled agricultural wastes, unless all the sewage from all the cities and septic tanks are also returned to the land without fertility loss, and there are no losses in the field. Since there will always be losses somewhere in the system, it is imperative that there be some synthesis of new nitrogen sources from somewhere, whether that be of biological or synthetic sources.

HOW NITROGEN IS LOST

Nitrogen can be lost from soil by a couple of processes. When soil becomes anaerobic (lacking in oxygen), there are bacteria that will strip the oxygen out of nitrate and convert it back into dinitrogen gas or nitrous oxide. Anaerobic conditions most often occur when there is standing water on a soil. Also, during excess water conditions, nitrate can be leached through the soil profile into groundwater.

Note that the primary form of nitrogen lost by both of these processes is nitrate. That is why I believe using a carbon-based nitrogen source, such as legumes in rotation or manure applications, is a great idea on any soil susceptible to standing

water or leaching. These sources will be broken down slowly into nitrate or taken up by plants before ever converting into nitrate—rather than forms of nitrogen that convert quickly into nitrate (such as synthetic nitrogen fertilizers).

Seeing Is Believing

During the flood season of 1993 in my area, the average irrigated corn yield was around 80 bushels an acre; it was typically close to 200 in a normal year. All of the nitrogen fertilizer was denitrified due to lack of oxygen because of the standing water, and the corn was horribly nitrogen deficient. The exceptions were the few fields I saw where corn had been planted in a freshly killed alfalfa stubble. Those fields produced normal yields despite the excess moisture.

When the water drained away, the fields that had to rely on synthetic fertilizer for their nitrogen needs were out of luck. In contrast, the old alfalfa fields had plenty of protein that began to decay and produce available nitrogen as soon as the oxygen levels were restored. These fields yielded just fine.

CAN NITROGEN FERTILIZER REDUCE YIELD POTENTIAL?

A few years ago, I had a world-famous soil scientist tell me that nitrogen fertilizer reduces yield potential. My first thought was, “That can’t be right.” In all of my previous experience, wherever I had seen a “skip” or gap in a fertilizer application, the soils that did not receive nitrogen fertilizer were horribly stunted and pale and yielded next to nothing.

As this scientist pointed out, however, my observations were made exclusively in a nitrogen-deficient environment, where plants were in desperate need of any nitrogen source. What about an environment that has an abundance of nitrogen in carbon-based forms, such as decaying protein? (Carbon-based fertilizer forms are discussed later in this chapter.)

The Road from Protein to Nitrate—and Back

It took some swirling around in my head for this to make sense, but it finally clicked for me. You see, when protein is added to soil, microbes extract energy from it and convert it into amino acids. More microbes then extract energy from the amino acids and change them into ammonium. One bacteria species will take energy from the ammonium and convert it into nitrite. Another bacteria species will take energy from the nitrite and change it into nitrate. Thus, nitrogen in the form of nitrate will have all the biological energy stripped out of it.

When the plant takes up nitrogen in the form of nitrate, it must add energy to convert nitrate into nitrite, then add more energy to convert nitrite into ammonium. A large amount of energy is then required to convert ammonium into amino

acids, and still more energy is needed to convert those amino acids into protein.

In most cropland soils the primary nitrogen source is nitrate, because all commonly applied synthetic nitrogen fertilizers, whether they supply primarily nitrate or urea or ammonium, are rapidly converted into nitrate by bacterial action in the soil. Nitrate is the only nitrogen source that is highly water-soluble and free to move in the soil with water (ammonium is a cation and binds to the negatively charged soil particles), so whenever a plant takes up water in a soil fertilized with synthetic nitrogen, it takes up nitrate. Then the plant has to use a great deal of energy (by some estimates as much as 25 percent of its total photosynthetic capacity) to convert this nitrate into protein.

Protein and Amino Acids

Obviously, this is better than having no available nitrogen at all, and in many cropland soils that is the alternative. But what if the soil is full of nitrogen in the form of protein and amino acids?

I was taught in college that plants take up nitrogen in the form of either nitrate or ammonium. This is mostly true: In most cropland it is true because there are so few other sources of nitrogen, and because amino acids are quite immobile and do not flow with water to the plants like nitrate does.

But plants are able to take up complex nitrogenous compounds other than nitrate or ammonium; if they could not, soil-applied herbicides that move into plants through root uptake (such as atrazine) would never work. And in addition to

having enough amino acids present in the soil to fulfill plant nitrogen needs, there must also be a mechanism for the amino acids to get to the plant.

ENTER MF

This mechanism happens to be colonization with mycorrhizal fungi. A bare root system occupies only 2 to 7 percent of the soil volume, but a root system colonized with mycorrhizal fungi occupies several times that volume and is equipped to explore every nook and cranny in the soil. It is quite adept at taking in amino acids and transporting them right into the vascular system of the plant root.

Theoretically, a soil supplied with abundant decaying carbon-based nitrogenous compounds (protein from plant residues or animal manure) and with an adequate population of mycorrhizal fungi should have a huge advantage in yield potential over a soil supplied with nitrate as the primary nitrogen source.

Because nitrogen is a nutrient that is mobile in plants, the bottom leaves will be the first to show symptoms of deficiency —a yellowing that first progresses along the vascular system of the leaves. (See Figure 4.1.)

Phosphorus (P)

The second most limiting nutrient in most systems is phosphorus, a component of all plant and animal byproducts, such as manure, sewage sludge, and particularly bone meal. While plants do not require large amounts of it, in most soils

the vast majority of phosphorus is tied up in unavailable compounds.

Soil pH is an important factor in P availability; in acid soil P is tied up in compounds with iron or aluminum, while in basic soils P is tied up in compounds with calcium. Maximum availability is obtained in slightly acidic to neutral soils.

Fertilizer P is created by mining apatite (rock phosphate) and treating it with acid to improve the availability and solubility of the phosphorus. Untreated apatite is perhaps 3 percent water soluble, while acidified phosphate is 100 percent water soluble.

The amount of minable rock phosphate worldwide is very limited, and known worldwide supplies are expected to run out within 100 years or less. This looming crisis is far more critical than the oil crisis, because other energy sources can easily replace oil. There is no substitute for phosphorus, and it is critical to all life on Earth.

Our current mass transfer of phosphorus from farmland and pastures to cities, in the form of food, and then toward the oceans, in sewage, is rapidly draining the world's supply at an alarming rate. Unless we develop methods to extract phosphorus back from the oceans, it may become a substance over which wars are fought. (See Figure 4.2.)

There is also a great deal of this element stored in the world's cemeteries, since bones of people are just as rich in phosphorus as bones of animals. Rumor has it that when Germany was cut off from phosphate mines in World War I, farmers resorted to grave robbing as a source of phosphate.

There is no substitute for phosphorus, and it is critical to all life on Earth. . . . Unless we develop methods to extract phosphorus back from the oceans, it may become a substance over which wars are fought.

IMPROVING PHOSPHORUS AVAILABILITY

Mycorrhizal fungi can greatly improve phosphorus availability. MF do not create the element, however; they just improve the uptake of it. Most commercial fertilizer is either diammonium phosphate (DAP, analysis 18-46-0) or monoammonium phosphate (MAP, analysis 11-52-0).

No matter the source, building up a good level of total phosphorus in the soil should be a priority: It may not be an option in the future. Under normal conditions in average soils, it takes as much as 18 pounds of fertilizer phosphate per acre to change the soil test level 1 ppm. The more biologically active a soil is, however, the higher the percentage of total phosphorus becomes available (using biology to make phosphorus available is discussed later in this chapter).

Phosphorus is typically quite immobile in the soil, moving only a few millimeters a year, and its movement is even slower in cold soils. Placement of phosphorus where roots can access it is quite important, therefore, especially in plants planted in early spring, such as corn, oats, peas, and potatoes. That is why P is such an important component of “starter” fertilizers that are applied relatively close to the seed.

Another issue regarding phosphorus fertility is that any water-soluble P applied to the soil is rapidly converted into

mostly unavailable forms. In acid soils it is converted into iron and aluminum phosphates, and in calcareous soils (soils with a high pH and excess calcium carbonate or limestone) it is converted into calcium phosphates. That is why P is usually applied at rates several times what the plant actually uses. There are many products that can be mixed with phosphorus fertilizers to maintain availability of phosphorus after application, including humic acid, fulvic acid, zeolite, diatomaceous earth, and sugar sources such as molasses.

Prospecting for Phosphorus

FROM THE COLONY (KANSAS) *FREE PRESS* IN 1886

May 27, 1886. Frank Denny, Louis Soule, Dan Yokum and Frank Walter left for the Indian Territory where they go in the employ of C.P. Walker to collect (bison) bones to be shipped north and ground up into fertilizers. It will be a paying business if the boys can find the bones, and there is no doubt of that. They took teams and wagons. Denny will boss the job.

Author's Note: Dan Yokum was one of my great-great grandfathers. One of his granddaughters married a grandson of Howard Hester (who dynamited soil [see here]), and the first child from that marriage was my father, Eldon.

PHOSPHORUS AND SOIL BIOLOGY

One problem with the application of phosphorus fertilizer is the impact on soil biology. Mycorrhizal fungi are particularly

helpful to plants in acquiring phosphorus. When plants suffer from a phosphorus deficiency, they "recruit" mycorrhizal fungi to colonize them by giving off a signaling molecule, called **strigolactone**, which causes the mycorrhizal spores to germinate. If plants receive too much phosphorus in a water-soluble form, they do not exude strigolactone, and mycorrhizal spores do not germinate.

Exactly what "too much phosphorus" amounts to is a matter of controversy. I have seen research studies that show this amount to be as high as 80 pounds per acre of water-soluble P_2O_5 (40 kg P/ha), but I have also heard of dramatically reducing colonization with as little as 15 pounds P_20_5 per acre (about 8 kg P/ha).

On the other hand, I have seen many examples of fields where mycorrhizal spores were mixed right into starter phosphorus fertilizer and the crop colonized quite well. I honestly don't know where the line is between enough P to meet crop needs and so much P that it interferes with mycorrhizal colonization.

The problem is that we feel we have to apply several times more phosphorus than the crop needs, because we know that chemical reactions will begin converting the water-soluble, highly available phosphorus we apply into unavailable forms as soon as it touches the soil. To ensure we have adequate P late in the growing season, we feel forced to overapply phosphorus at planting; and since phosphorus is quite immobile in the soil, we can't effectively apply it later in the growing season and get it into the root zone without tearing up the roots.

POSSIBLE SOLUTION

Perhaps a better way to apply phosphorus fertilizer is to apply lesser amounts but in a different form, a form that maintains availability late into the season but is not water soluble and will not reduce strigolactone production in the plants. A partial solution may be to mix in additives (such as molasses and humic acid) that help maintain phosphorus availability later into the season. These additives enable microbes to convert the water-soluble phosphate into different forms that are still plant available but not water soluble. Colloidal phosphate and soft rock phosphate are water insoluble and do not reduce mycorrhizal colonization.

Potassium (K)

The third most common limiting nutrient, potassium, has the same function in plants that sodium has in animals, to act as an osmotic regulator. It is important in drought tolerance, frost tolerance, and a host of other functions. Potassium is not tied up in soil to the extent that phosphorus is, but it is still largely unavailable, and plants require large amounts of it. (See Figure 4.3.)

Some soils have a natural mineralogy that provides plenty of K; others do not. Typically, soils with recent volcanic or glacial origin rich in feldspars are high in potassium. Soils of the southeastern US are notoriously low in K, while soils in the western Great Plains are typically high. Grain is very low in K, but plant vegetative material is high. Grain cropping removes little K, while hay or silage removes very large amounts.

Animal bodies are fairly low in K because most of the K eaten is excreted. Manure and urine contain considerable K, as do composted plant wastes and sewage sludge.

Wood ash is a decent potassium source, ranging up to 8 percent K by weight, and is occasionally locally available in usable quantities. Wood ash in large quantities can dramatically raise soil pH and should be used only on acidic soils. Luckily, the areas with acidic soils also tend to be the ones with the most forest cover, where wood ashes are most readily available.

Fertilizer sources of potassium include the widely available potassium chloride (KCl, or 0-0-60). A less widely available but excellent source of potassium is potassium phosphate, a material that is expensive, so it is usually reserved for high-value crops for which KCl is not suited. Potassium chloride is not well suited for tobacco, as it makes the tobacco retain too much moisture and makes it hard to burn. Other sources of potassium include kelp and some powdered rock, such as greensand or granite meal.

Sulfur

Increasingly deficient in farm soil, sulfur is necessary for plants to convert nitrate and ammonium into protein, used in a ratio of about 1 part sulfur for every 10 to 15 parts nitrogen. Lacking sulfur, plants will often take up nitrate by mass flow but not change it into protein, possibly resulting in levels of nitrate that are toxic to livestock consuming the plants. (See Figure 4.4.)

Prior to the passage of the Clean Air Act, sulfur was a pollutant in the atmosphere, from the burning of diesel fuel and the coal burned in electrical power plants. There were agronomically effective rates of sulfur (in the form of sulfuric acid in rainfall) deposited in rainfall over most of the eastern United States, downwind from population centers. This pollution no longer occurs, which obviously is a good thing overall, but it creates a need for sulfur fertilization.

Soil tests for sulfur are not at all reliable, because sulfur, like nitrogen, exists in largely organic form, and the breakdown and release of it is quite variable and depends on biological processes.

Sulfur can be provided in elemental form but must be converted into the sulfate form to be taken up by plants. Conversion of sulfur into sulfate is also a biological process and requires the bacteria *Thiobacillus*, which becomes more prevalent with frequent use of elemental sulfur. Sulfur can also be provided in sulfate form in commercial fertilizers such as ammonium sulfate, ammonium thiosulfate, potassium magnesium sulfate, and so on. It is also found in any protein-containing plant or animal residue or manure.

Finally, gypsum is calcium sulfate, and therefore a source of both calcium and sulfate, though it is slowly soluble. A ton of gypsum per acre can supply sulfur for a couple of decades. Sulfur oxidation causes soil to acidify, but gypsum is already oxidized and has a neutral effect on soil pH.

All Tied Up

When iron gets converted into forms that are not available to plants, it is **tied up**.

Calcium

Most common on tomatoes, where it is responsible for blossom end rot, calcium deficiency is seldom considered limiting as a plant nutrient, while an abundant supply of soil calcium is a tremendous aid to soil biology, primarily earthworms. Calcium aids soil aggregation, as it is a **divalent** (with two positive charges) cation that can attract two adjacent clay particles together. It is also a necessary component of calcium-polysaccharide complexes found in the earthworm slime and microbial slimes that glue soil aggregates together. Calcium can also be valuable as a foliar nutrient, helping fill gaps in between cells on the leaf surface and providing a barrier to fungal infections.

In acidic soils, calcium can be supplied with ground limestone, and in neutral or alkaline soils with gypsum. Wood ash tends to be almost 30 percent calcium.

Iron

Iron is quite often a limiting nutrient in higher-pH, calcareous (having an excess of calcium carbonate) soils, as the form of iron in the soil is converted from the more available Fe++ to the lesser available Fe+++.

Soybeans, sorghums, and pin oaks are particularly susceptible to iron deficiency. The deficiency in sorghum is most severe, as the calcareous soils are usually found in droughty areas where sorghum is otherwise best adapted. (See Figure 4.5.)

Traditionally, iron deficiency has been treated by the following methods:

- Apply foliar iron at the rate of 1 to 2 pounds per acre of iron sulfate in solution, or a lesser amount of a chelated (carbon-based) iron solution. Iron is moved around poorly within plant tissue, so although iron is absorbed through the leaves well enough, as new leaves emerge, they are as iron deficient as the older leaves were prior to spraying. Foliar spraying works well if repeated at frequent intervals at relatively low application rates, because the iron never touches soil. Touching the soil would begin to convert the iron into unavailable compounds, a process known as tied up.
- Provide large manure applications. The organic compounds formed upon manure decay act to chelate the iron into organic forms that are less subject to being tied up by calcium carbonate.
- Select crop species and varieties more tolerant of low-iron conditions. Most seed dealers of sorghum or soybean

varieties have ratings of their varieties for susceptibility to iron deficiency.

- Make in-furrow applications of chelated iron fertilizers. These provide only temporary benefits before the iron is tied up by the soil, but they can allow the seedling to develop enough of a leaf canopy to intercept some foliar-applied iron.

MORE WAYS TO IMPROVE IRON AVAILABILITY

It is becoming increasingly apparent that there are other and more efficient ways to improve iron availability. The best results are obtained by combining several of these techniques together. Every year that this battle is fought, the amount of iron in organic forms (available to plants but not subject to chemical reactions in the soil that reduce availability) becomes more abundant.

Here are some of the more promising methods.

Cover Crop Options

Take up excess nitrate in the soil prior to growth of the cash crop by using cover crops. This process works because plants must remain electrically neutral; if they take up a cation they have to give off an H+ ion to counter the charge. If they take up an anion, they have to exude a bicarbonate ion (HCO_3-) in order to counter; this ion will dramatically reduce the availability of iron in the rhizosphere. Since nitrate (NO_3-) is negatively charged, allowing plants to take up nitrate as the nitrogen

source results in a large amount of bicarbonate in the rhizosphere and poor iron availability.

Using a cool-season annual grass cover crop, such as barley, prior to growing soybeans results in a low-nitrate condition. This forces the soybeans to get nitrogen as ammonium from their nodules instead of using nitrate from the soil.

Prior to a nonlegume cash crop, legumes can be used as a cover crop. Even though they enrich the soil with nitrogen, this N is in the form of protein and will be first (and slowly) broken down into ammonium, thus providing nitrogen without saturating the soil with large amounts of nitrate at any given time.

Sweet clover is a legume that exhibits excellent tolerance to soils prone to iron deficiency and has good value as a green manure prior to sorghum or other nonlegume crops susceptible to iron deficiency.

Microbes and Mycorrhizal Fungi

Another exciting tool in the availability of iron on calcareous soils is the use of microbes. Mycorrhizal fungi can greatly improve iron uptake, and there are a number of microbes that can produce siderophores, a form of iron chelate, in the rhizosphere.

Streptomyces lydicus is a commercially available microbe with the trade name Actinovate that produces siderophores. Inoculation with mycorrhizal fungi is a no-brainer for improving uptake of iron, while there are a number of other microbes that also show promise, such as *Azospirillum*.

Magnesium

Magnesium is not often limiting for plant growth but is sometimes at such low levels in plant tissue that grazing livestock develop a hypomagnesium condition called grass tetany, which results in staggering, poor coordination, and, occasionally, death. This condition is most common in cool-season grasses in early spring with colder soils. Oddly, low magnesium in plant tissue is not often helped much by soil fertilization with magnesium, but rather by fertilization with phosphorus. Phosphorus appears to greatly aid magnesium uptake, while excess potassium appears to reduce it. (See Figure 4.6.)

Foliar fertilization appears to be effective, but there is a limit to the amount that can be supplied in this manner. Methods of improving magnesium fertility hold promise for greatly improved cool-season grass productivity. The most common soil-applied magnesium fertilizer is magnesium sulfate (Epsom salts) while the foliar-applied sources are magnesium chloride or magnesium nitrate. To correct the deficiencies in grazing animals, magnesium supplementation in the mineral is usually advised.

Zinc

Grazing animals are often zinc deficient unless they are supplied with a mineral supplement enriched in zinc. Excess phosphorus can cause zinc to be deficient.

Crops most likely to be deficient in zinc are corn, sorghum, and pecans. It is often deficient on high-pH, eroded, or other low-organic-matter soils, and zinc fertilization of the soil is very effective. Virtually any plant- or animal-based residue, such as manure or yard waste compost, is also effective at boosting zinc availability. Zinc sulfate is a common source, but zinc chelates are becoming more popular because they require lower use rates.

For best results, apply zinc close to the seed, as with an in-furrow application. Add with foliar applications if deficiency symptoms appear. (See Figure 4.7.)

Manganese

In the past, manganese was seldom a concern, but it has recently come into the spotlight. This is due to the widespread adoption of GMO crops containing a gene that provides tolerance to glyphosate herbicide (trade name Roundup). It has been found that Roundup Ready crops (crops genetically engineered to tolerate Roundup) do not translocate manganese well, nor do they take it up well from the soil. (See Figure 4.8.)

Additionally, it appears that this poor manganese uptake affects the crop *following* the Roundup Ready crop, perhaps because of changes in the microbial community. Manganese fertilization is effective either through soil as manganese sulfate or foliar with manganese nitrate or manganese chelates.

Copper

Copper is a nutrient of most concern on small grains. And while it is seldom a concern for production of forage crops, at least in the US, the copper content of forage crops is often too low for optimum livestock nutrition. Black-haired cattle exhibit copper deficiency as a reddish tinge to their hair.

Oddly, copper availability is often reduced as soil organic matter increases, through mechanisms not well understood. Virtually all other mineral nutrients are made more available as soil organic matter increases. Since soil-building efforts focus on increasing organic matter, copper availability may be more of a concern in the future if you follow the advice in this book and are successful in increasing soil organic matter.

Copper can be supplied through soil-applied copper sulfate or by foliar application of copper sulfate or copper chelates. Copper supplementation in the livestock mineral supplement is often advisable. The best way to diagnose copper deficiency in livestock is to analyze a liver sample taken postmortem. The hair and blood samples that can be used to diagnose other livestock mineral deficiencies are not very accurate in diagnosing copper deficiencies.

Molybdenum, Chloride, and Boron

Molybdenum is seldom limiting for plants themselves but is required for the bacteria that fix nitrogen on legumes. In areas with low molybdenum, adding it to legume inoculants is common. Molybdenum is also necessary for plants to convert

nitrate into protein, so adding just a little molybdenum to forage crops susceptible to nitrate toxicity for livestock can reduce nitrate levels.

Chloride is another nutrient coming into more prominence. Since chloride is a component of the potassium chloride often used to supply potassium, areas with low potassium have had a history of potassium chloride fertilization and have no need for chloride fertilizer. But areas with high natural potassium levels, which have not received potassium chloride in the past, have shown good responses to chloride fertilization. Chloride also seems to slow the development of several plant diseases, particularly leaf rust on wheat.

Boron is often most limiting in areas where soils have leached out, either because of high rainfall or because of sandy soils. It is most important for root crops (such as turnips and radishes) and legumes. Boron can be toxic in excess amounts, particularly to germinating seedlings, so care must be used to not overdo it and to apply it as a broadcast solution to avoid areas of concentrated boron. It should therefore never be applied in the seed furrow. The most common source of boron fertilizer is borax. (See Figure 4.9.)

Nickel and Cobalt

Nickel is a part of the enzyme urease and is important if urea fertilizer is used, particularly as a foliar spray. The urease enzyme allows the plant to process very large amounts of urea fertilizer without suffering from leaf burn, especially if applied as a foliar spray.

Cobalt is not a plant nutrient but is necessary for many bacteria. It is an essential part of the vitamin cyanocobalamin (vitamin B-12), which is essential for most higher animals. In animals with fermentating digestive systems, such as ruminants, the bacteria can synthesize vitamin B-12 as long as they have cobalt. Only tiny amounts are needed, but this tiny amount must be present or no B-12 is made.

Carbon-Based Fertilizers and Soil Amendments

It is very easy to make soil better. Simply import a whole bunch of organic material and dump it on the soil. Presto! Better soil. This process is described in every single book on improving soil. There is only one problem with this approach: Those organic materials were brought from somewhere, and that "somewhere" is getting deprived of that organic matter input. These materials do not produce organic matter; they transfer it.

I much prefer growing the material right in place, rather than robbing one location to enrich another and using fossil fuel to transport it. However, the fact remains that millions of pounds of valuable materials are simply tossed into oceans, rivers, or landfills across the world when they could be used to build soil somewhere. It is essential that these materials be used, rather than simply disposed of. Some of these materials

are organic in nature, others are mineral sources. Here is a rundown of some of those materials.

Manure

Manure is simply the fecal matter and urine from livestock. Manure is often considered to be a fertilizer, and indeed it does contain an appreciable amount of minerals, depending on the species of animals and what they are fed, but it takes literally tons of manure an acre to provide all the mineral nutrients a crop requires. Remember, manure contains no nutrients that were not in the feed of the animal at some point, so the more nutrients the feedstuffs have, the more nutrients the manure will have.

Manures, like most of the other carbon-based fertilizers discussed here, have value far beyond their value as a fertilizer. I saw a research trial done over 30 years ago in Kansas. A single application of manure was made to a field, and the yield of crops over a 10-year period was measured. The field was also heavily fertilized, so the nutrients contained in the manure likely did little to improve yields, as the soil contained all the fertility (at least of all the major nutrients) the crops could possibly hope to use, and any yield increase the crops would demonstrate would be the result of factors other than the mineral fertility of the manure.

I calculated the value of the fertilizer in the manure, at 1990 prices for fertilizer, to be about $5 per ton of manure, based on the analysis. But the yield increase per ton of manure over the 10 years of the study was worth $25 a ton, again at 1990 crop

prices (which sadly are not much different from current prices). It was also interesting to see that the yield increase from the one-time application of manure at the beginning of the study appeared to be just as strong in year 10 as it was in year 1. The point is, the main value of manure and other carbon-based fertilizers is not so much their mineral nutrient content; it is all the "other stuff" they contain, mainly microbes and a food source for microbes.

HANDLING MANURE

How manure is handled is important. The most efficient way to handle manure is to not handle it at all, and instead manage and locate animals so the manure is deposited where fertility is needed. It is easier and cheaper to haul feed to animals on the field than to haul feed to animals in confinement and then gather and haul manure to the field.

Manure deposited on a field has more benefit if there are manure-consuming organisms present, such as earthworms or dung beetles. Manure left on the soil surface can lose up to 50 percent of its total nitrogen content to the air due to volatilization. The ammonia smell from manure is exactly that: ammonia, a valuable plant nutrient, being lost to the air. This loss can occur whether animals are in confinement or on pasture, but on pasture it is possible to enlist an army of willing insects and earthworms that will help minimize the losses.

Another way to minimize nitrogen losses from manure is to feed the animals charcoal, which can absorb ammonia in the manure before it is deposited. Charcoal in feed can also reduce

the odor of manure and has feed-efficiency benefits for ruminants. Potassium is a nutrient that can be lost from manure in outdoor confinement on soil but can be conserved when animals are on the field, as potassium is highly soluble and is washed out of the manure with rainfall. Systems in which animals are kept on slats, in which the manure and urine are contained in an impermeable (i.e., concrete) receptacle and applied later to the field, can retain nearly all the potassium in the manure, but in these systems nitrogen losses from volatilization can be high.

MINERAL CONTENT OF ORGANIC (CARBON-BASED) MATERIALS*

MATERIAL	% N	% P2O5	% K2O	C:N RATIO
Alfalfa hay	3.0	0.2	2.0	13:1
Ashes, wood	0	0.9	5.0	NA
Bat guano	10.0	2.0	1.7	NA
Blood meal	13.0	0.7	0.7	3:1
Bone meal	4.0	10.1	0	NA

*Comparing percentage of nitrogen, phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O) on a dry weight basis

Source: "Let's Take a Look at Organic Gardening," Ohio State University Cooperative Extension Service, Extension Bulletin 555, 1973.

MINERAL CONTENT OF ORGANIC (CARBON-BASED) MATERIALS*

Cottonseed meal	6.0	1.1	2.3	7:1
Fish meal	10.0	2.6	0	4:1
Kelp	0.6	0	1.1	70:1
Manure, cattle	2.0	1.0	2.0	20:1
Manure, hog	2.0	0.6	1.5	20:1
Manure, horse	1.7	0.3	1.5	24:1
Manure, poultry	4.3	1.6	1.6	9:1
Manure, sheep	4.0	0.6	2.9	10:1
Sawdust	0.2	0.01	0.2	200:1
Sewage sludge	5.0	2.2	0.4	8:1
Soybean meal	7.0	0.5	2.3	6:1
Wheat straw	0.6	0.1	0.9	70:1

*Comparing percentage of nitrogen, phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O) on a dry weight basis

Source: "Let's Take a Look at Organic Gardening," Ohio State University Cooperative Extension Service, Extension Bulletin 555, 1973.

COMPOSTING MANURE

Composting manure offers some benefits. Composting creates a stable, relatively pleasant-smelling product that is more concentrated in most mineral nutrients than raw manure and does not emit ammonia gas. Fresh manure can actually kill seedlings due to the burn from ammonia it releases. The downside of composting is that much of the ammonia and energy contained in the manure can be lost during the composting process.

Another advantage of composting, as discussed later, is that the process can be guided to create whatever form of microbial population is desired. The table opposite gives some information on the composition of different forms of raw manure and other carbon-based fertilizers.

Utilizing Sewage

Sewage is the fecal matter and urine of people, along with whatever else gets flushed down the drain and sewers. Water-based treatment and disposal of sewage has always been considered "modern" and sanitary and has greatly reduced the spread of diseases transmitted through human waste. However, it has also resulted in large amounts of mineral fertility being dumped into oceans, particularly at the mouths of rivers. This accumulation of excess fertility has resulted in algal blooms and subsequent oxygen depletion, which has been quite damaging to aquatic life in many previously productive areas. (See Figure 1.5.)

POTENTIAL HAZARDS IN SEWAGE SLUDGE

Ideally, all of the nutrients and organic matter in sewage sludge would be returned to the fields to prevent their loss to the ocean—and the material would be free of harmful effects. In reality, however, there are several harmful materials that can be present in sewage sludge.

Heavy metal contamination, such as lead and cadmium, is the first hazard, originating not in human feces but in industrial products that also get flushed down the pipes. Lead and cadmium can cause major health issues for both animals and people, and any sewage sludge applied to land used for food should be tested for heavy metals.

Human pathogens, such as *E. coli* or *Cryptosporidium*, are another potential hazard. The easiest way to eliminate these pathogens is through a period of controlled decay, in which the pathogens are simply eaten by other microbes. Most modern sewage treatment involves a period of aeration and stirring designed to eliminate pathogens. Even so, occasionally some pathogens survive this treatment. Therefore, it is wise to apply sewage sludge to crops in which the edible portion does not actually contact soil, such as fruit trees, or to crops that are not directly consumed by humans, such as cotton or pastures. It is also best to apply sewage sludge at least six months before harvest of any crop, as pathogenic organisms are simply eaten over time.

Pharmaceuticals are a third potential hazard. For example, antidepressants are now found in biologically effective levels in some sewage sludges and have been found to reduce

reproductive success in geese that frequent sewage ponds. While many of these compounds will break down naturally over time in the soil (antibiotics, for example, are usually derived from naturally occurring soil organisms, so there are organisms in soil able to process them), we don't know if that is true for all pharmaceuticals. More research is needed on this matter.

LEARNING BY DOING

A Great Deal

A few years ago, I received what I thought was a great deal. A nearby town offered me all of their lawn waste that had accumulated for about 20 years, free for the hauling. I took a sample of it and sent it to a soil test lab, and the nutrient content was impressive, so I ponied up a few thousand dollars to have it hauled and spread onto my farm. According to the soil test, I should have had enough fertility to last for several years of crops from this single application.

The first crop I planted after the application was sudangrass, and I was so excited to see the results. To my dismay, the sudangrass came up and looked yellow and sickly and was soon overtopped with a solid stand of weedy barnyard grass—in a field where I had never seen barnyard grass. That summer, my cows had to eat barnyard grass instead of the high-dollar, brachytic dwarf,

brown midrib sudangrass that I had planted. I was left wondering what happened.

I consulted a friend of mine who made compost himself and knew a thing or two about it. He asked me how the compost smelled. “Awful,” I said, “like rotten silage.” Then he asked how often the compost was turned. I told him it was never turned, just pushed into an ever-growing pile. Finally, he asked what plants grew after I applied the compost. I told him about the barnyard grass.

He concluded that this “compost” was anaerobic, and the rotten silage smell was butyric acid, an undesirable acid formed by anaerobic organisms. He explained that barnyard grass is a weed common to water-saturated soils because it is tolerant of anaerobic conditions that produce butyric acid and ethanol in the soil. My sudangrass was not tolerant of these conditions.

As it turns out, the free compost wasn’t such a good deal and cost me greatly that year. The next year, however, this field exploded with growth, after the butyric acid and ethanol were metabolized by microbes into less detrimental or even beneficial compounds and yielded almost 50 percent more than the part of the field that did not receive this material.

Compost

The product of the carefully controlled decay of organic materials, compost is a source of both mineral nutrients and organic matter. Its true value, however, is as a microbial inoculant. The types and abundance of microbes contained in compost depends on the materials from which it is made as well as by the specific composting process used. Temperature, aeration, raw materials, and frequency of turning all have major impacts on the value of the compost. There are now various schools of thought when it comes to concocting compost, and many people have their own "secret recipes."

Following are some key considerations.

AERATION

Decay uses up oxygen, and unless there are measures for ensuring adequate oxygen content, a compost pile will go anaerobic and result in undesirable organisms, often producing products such as ethanol and butyric acid, that are toxic to plant roots. The traditional method of ensuring oxygen content is frequent turning of the pile, but now there are alternative means of aeration that are worth trying, such as perforated drainage tubes buried within the silage pile.

Another approach to compost making is to go the complete opposite direction and make a compost that is totally anaerobic and inoculated with beneficial anaerobic microbes prior to sealing off the pile from oxygen. Probably the most well-known anaerobic bacteria are *Lactobacillus* species similar to the organisms that make sauerkraut and pickles. An anaerobic pile can make a lactic- acid-preserved compost silage, and lactic acid can have some very desirable effects on the soil.

On a larger scale, anaerobic compost making has been championed by Gerry Gillespie of Australia (see here). It has been found that this particular lactobacillus-rich form of compost contains "autoinducer" compounds that greatly stimulate seedling vigor and colonization of seedling roots by beneficial microbes when applied to seed, either as a seed treatment or as an in-furrow treatment at planting.

How to Make Bokashi

Bokashi is a form of anaerobic, lactic-acid-producing, small-scale composting designed to process kitchen wastes into a sort of "pickled garbage" compost that is relatively odorless. This method produces a very fine compost for backyard garden use.

1. You need three 5-gallon buckets. Drill a hole into one bucket to allow liquid drainage. Insert it into a second bucket to catch the drainage.
2. Put kitchen waste into the double bucket. Sprinkle a lactic acid starter culture (sold commercially as "EM," which stands for "effective microorganisms") on top.
3. Slide another bucket over (on top of) the double bucket to prevent oxygen entry.

FREQUENCY OF TURNING

As stated previously, the traditional method of aerating a compost pile is to stir it. While this certainly does the trick for aeration, turning tends to tear apart fungal hyphae and results in a compost that is dominated by bacteria.

Since most agricultural soils are low in beneficial fungi and the goal of adding compost to a soil is to inoculate the soil with desired organisms, a composting method that does not involve as much turning may be desirable. This is the basis for the Johnson-Su method (see Making Johnson-Su Compost), in which aeration tubes are placed in the pile and turning is limited, with the intent to culture a fungal-dominated compost.

C:N RATIO

A material that is high in protein (low C:N) will decay very rapidly, while a low-protein (high C:N) material will decay very slowly. In general, high-protein materials are green, and low-protein materials are brown.

Often it is advised to blend low-protein and high-protein materials together for an intermediate speed of decay. An example would be layering grass clippings (high protein) with wood chips (low protein).

See table providing the C:N ratio of several materials.

RAW MATERIALS

Almost anything of animal or plant origin, and even many minerals, can be tossed into composts. There are procedures

for composting dead animals and turning them into a high-nitrogen, high-phosphorus organic fertilizer. This produces microbes capable of breaking calcium phosphate molecules (the mineral component of bones, and a form of calcium in the soil unavailable to plants) apart to make both the calcium and the phosphate available to plants. Once composted after six months to a year, the entire animal, bones and all, is converted into a crumbly, black, moist, and relatively odorless powder.

Rock dusts of various kinds can be put into composts, with two goals in mind: allowing microbial action to release mineral nutrients from the powdered stones, and culturing microbe populations capable of releasing fertility from rock particles in the soil. Basaltic rock powders are especially coveted due to their high content of plant nutrients relative to other rocks. Adding rock phosphate or colloidal phosphate to compost can also greatly add to its value. Other additions might be sugar sources, like molasses, or ocean products, like kelp.

Soil, particularly heavy clay soil, is sometimes added to compost to help trap and sequester volatile nitrogen compounds that might be lost from the pile during the composting process, and to create a humus-clay complex that makes a particularly good potting soil. Soil is also (literally) dirt cheap, so it can be used to bulk up compost volume in an inexpensive manner.

Woody debris and other materials high in lignin are particularly good for creating a compost high in fungi; as in nature, fungi are the only organisms that degrade lignin. Since many fungi offer particular benefits for soil structure—and most agricultural soils are very low in fungi, due to a history of tillage—using wood chips or other lignified material as a raw

material can be very desirable. Charcoal can have similar benefits as clay when added to compost.

HOT (THERMAL) COMPOST

A compost with a fairly high percentage of high-protein material that is aerated often will become very hot during the decay process. This heating kills the spores of many plant pathogens and destroys weed seeds. Compost made in this manner is called thermal compost. Thermal composts involve careful monitoring of pile temperature, with a target range of 140 to 160°F. As a pile reaches 160° it is turned to eliminate "hot spots."

Thermal composting can make compost very quickly. A potential drawback is that desirable organisms may be destroyed along with the pathogens. Cool composting involves a slower decay without such a heat rise. Thin-layer, static composting involves spreading compostable materials in a thin, well-aerated layer without turning, mimicking the decay process that occurs on a forest floor, and in which hot temperatures do not occur.

MAKING THERMAL COMPOST

The thermal composting method is widely used and makes a very good compost in general for most purposes. Dr. Elaine Ingham is an expert when it comes to compost making. Here is a list of compost-making instructions for a thermal compost, based on the Elaine Ingham school of thought:

1. Gather three basic ingredients: green material (such as hay or lawn clippings, chopped weeds, or any other fresh plant material), brown material (such as straw, wood chips, or other high-lignin material), and a material that is relatively high in nitrogen (animal manure is commonly used for this).

2. Mix the three materials in relatively equal proportions so they are well blended.

3. Moisten the materials enough so that you can make a ball and squeeze the water out of it, but not so much that water runs out of the pile by gravity. (This will be around 50 percent moisture.)

4. Cover the pile with an air-permeable but moisture-retaining tarp, such as landscape fabric.

5. Maintain a pile temperature between 140 and 160°F (60 and 72°C). If the temperature nears 160°, turn the pile. On the other hand, if the pile will not heat, add some high-nitrogen material (nitrogen fertilizer or a high-nitrogen organic material such as urine).

6. When the compost finally begins to cool, it is nearing the end of the composting process. When temperatures drop down to around 100°F (38°C), it should be ready for use.

Putting Heat to Work

Years ago, a French farmer named Jean Pain observed the amount of heat coming from his compost pile and decided to put that heat to work. He ran water pipes through his pile and used the heat of the composting process to heat his domestic hot water!

Since then others have caught on to the act, and some people have figured out that you can use perforated drainage tubing run through a compost pile with a fan at the end to pull air through the tubing into a greenhouse. This not only heats the greenhouse but also pulls oxygen air into the compost pile through the vacuum created and simultaneously introduces carbon dioxide–rich air into the

greenhouse to boost photosynthesis. Yes, even the heat and carbon dioxide generated during the composting process can be put to use.

INOCULATION

The addition of microbes to a pile has often been likened to throwing a bucket of water in the ocean. Tossing a few pounds of microbes into a thousand-ton pile of microbes may seem to be a wasted effort but can be quite useful under certain circumstances. Introducing some organisms can be useful right before the conditions of the composting process change. An example is the introduction of lactic acid starter culture just prior to excluding oxygen from the pile; or the introduction of mesophyllic (adapted to moderate temperatures) organisms right when a thermal compost is beginning to cool and is populated only by thermophyllic (heat-loving) organisms.

MAKING JOHNSON-SU COMPOST

Johnson-Su compost is a specialized form of compost used primarily to create extracts that serve as highly effective microbial inoculants. The Johnson-Su process is very low-disturbance, and the pile is not turned during the composting process (also called a static compost). It is also highly aerobic. This combination of aerobic conditions and lack of disturbance combines to create a compost that is exceptionally rich in desirable fungal spores.

Dr. David Johnson (for whom the process is named, along with his wife, Su) has documented how creating a soil with a better fungal-to-bacterial ratio can greatly aid soil productivity, including drought resilience. Because the main purpose of this process is to produce compost extracts rather than compost for direct application, a small amount of compost can be used to create a very large amount of extract that can cover a very large land area (or be applied to a very large amount of seed) so it becomes an extremely economical means of soil improvement.

The process involves building a compost pile within a piece of landscape fabric (which is permeable to both air and water vapor) contained within a wire mesh container wrapped in a circle to form a cylinder, and with aeration tubes placed vertically within the pile to ensure the entire pile has adequate oxygen. (See Figure 5.1.) Then, the pile is left to sit untouched for roughly 12 months, which is a very long time in the compost world, but this is a slower process than making a highly bacterial compost.

LEARNING BY DOING

Whatever It Was, It Worked

I received an excited call one day in March from my friend Shane New, insisting that I stop by to see something. When I arrived, he showed me the compost pile that he had made with what he called the “Johnson-Su process.” I have seen

compost piles before, so I failed to understand the urgency. Then he said he wanted to show me his pasture.

As I approached, I could clearly see on the hillslope a black streak exactly 30 feet wide going through his pasture, and the grass in this dark strip was double the height of the grass on either side of this strip. Since burning pasture in the spring to stimulate new growth is a common practice in Kansas, I asked him how he was able to burn a strip so precisely that wide. As we got closer, he grinned with glee and said, “I didn’t burn this. That is where I applied that Johnson-Su compost a couple weeks ago.”

We got out and inspected the strip, and the thatch remaining from the previous year’s growth was rotted completely black, looking like it was burned, but it was still intact. And the soil within this strip was noticeably warmer than the soil where the compost was not applied, perhaps from sunlight hitting dark-colored material instead of pale gray thatch, or perhaps because of heat generated from the obviously enhanced microbial activity.

Whatever it was, it was working, as evidenced by the grass that was almost exactly double the height of the surrounding grass. If you have ever been at the end of winter and running low on hay and praying that the new grass comes on fast enough to graze before your hay supply runs out, you know how significant this achievement is in the month of March.

WAYS TO USE COMPOST

There are four basic ways to use compost:

As a growing medium. Compost can be used as a potting soil, especially if a relatively large amount of soil was added during the composting process to form a "humus compost." This is widely used in greenhouse applications and other very high-value crop situations.

Adding directly to soil, spread "as is" with a manure spreader. This provides a very high level of impact per acre but is also costly, as the amount applied is ordinarily very high per unit land area.

As a compost extract. This is a practice in which a small amount of compost is placed into a container of nonchlorinated water and agitated. The coarse compost material is strained out, and the liquid is sprayed out to serve as a microbial inoculant. Alternatively, this liquid can be used to moisten seeds before planting. Both methods are very effective at introducing beneficial organisms to relatively large areas of land at minimal cost.

As compost tea. This process creates a very microbially dense liquid that can be sprayed either on the soil or as a foliar application to a crop. Compost teas have much greater microbial density than compost extracts, but since not all

organisms tolerate the brewing process equally, the microbes are less diverse in compost teas.

Compost teas may have their highest use when sprayed on a crop as a foliar application, because the extremely high density of benign and beneficial microbes can not only act as a foliar fertilizer, but it also seems to produce an antibiotic, antifungal barrier that protects plants from foliar leaf diseases. I know several organic farmers who use compost tea applications in lieu of chemical fungicides to protect from leaf rusts on wheat, or gray leaf spot in corn, or as a general foliar disease preventive on high-value crops.

One Way to Make Compost Tea

To make a compost tea you put a compost extract into a "brewing" process. Provide a way of stirring or aerating the tea (such as a bubbler used in live wells on fishing boats), and add food compounds to nourish the rapid growth of microbes that will follow. Those foods might be molasses (for sugar), fish hydrolysate (for protein and lipids), and kelp meal (for trace minerals).

[T]he extremely high density of benign and beneficial microbes can not only act as a foliar fertilizer, but it also

seems to produce an antibiotic, antifungal barrier that protects plants from foliar leaf diseases.

HOW TO MAKE ANAEROBIC COMPOST

Anaerobic compost is a large-scale form of Bokashi, used to make a compost high in *Lactobacillus* and lactic acid.

INGREDIENTS (AMOUNT IN EQUAL MEASURES)

- **1** Rice or other grain
- **4** Water
- **8** Milk
- **2** Molasses

MATERIALS

- Any plant materials to be composted
- Water free of chlorine
- Plastic tarp
- Widemouthed jars and lids

INSTRUCTIONS

1. Make a lactic acid starter culture:

- Put 1 measure rice or other grain in 4 measures water in a jar with tight lid; shake vigorously for 100 seconds, then loosen the lid and allow the mixture to sit for 3 to 5 days.
- Pour off the water into a container, and discard the grain.
- Add this liquid to 8 measures of milk, in a widemouthed jar, cap loosely, and let sit for 3 to 5 days.
- Pour off the liquid into a clean container, fill with an equal amount of unchlorinated water, and add 2 measures of molasses. After a few days this will be an effective starter culture and should last for a year or more.

2. Gather compostable materials (any plant-based materials), trying to maintain a carbon-to-nitrogen ratio of roughly 25:1 (see carbon-to-nitrogen ratio table).

3. Mix the materials thoroughly and moisten with the compost starter solution in a ratio of 1 part starter to 2,000 parts unchlorinated water. Try to achieve a moisture level of 50 percent, which can be determined easily by holding a ball of the material and squeezing: At 50 percent moisture, just a few drops of water will ooze out and drip.

4. Place the mixed material in a pile or windrow with a slight dimple or valley in the top. Cover the pile with a durable plastic tarp, and seal it tightly to the ground to prevent the entry of oxygen. Allow the pile to ferment for 12 to 16 weeks.

After fermentation is complete, this compost is useful for making extracts (see Ways to Use Compost) suitable for application to seed (it is very effective at stimulating seed germination and early development), in furrow at planting, or for soil application.

OPTIONAL STEP: Make a More Complex Inoculant

INGREDIENTS	AMOUNT IN EQUAL MEASURES (LBS, KG, ETC.) TO TOTAL 416 MEASURES
Lactic acid starter culture	20
Nonchlorinated water	350 or more on hand
Green plant material	40
Blood meal	3
Bone meal	3

Bran or ground grain	6
Basalt dust	2
Kelp meal or liquid kelp	2
Molasses	6
Clean container that can be loosely covered	

A. Add all ingredients to container, cap loosely to allow gases to escape but to prevent entry of other microbes. Alternatively, cap with a fermentation lock.

B. Tighten cap and shake or stir once daily for five days. After five days this product should be ready to use.

C. Prior to use, pour through a strainer or filter (coffee filter, cheesecloth, etc.) to remove coarse materials.

Wood Products

Historically, wood products have been considered to have little value as a soil amendment. That's because they contain a very low amount of the minerals we most desire to add to soil (nitrogen, phosphorus) and a very high ratio of carbon to

nitrogen, which means these materials tend to tie up nitrogen upon decay. Nowadays they are viewed in a much more favorable light, as we begin to value carbon-based materials not as sources of mineral fertility, but for their effects on soil physical properties and biological properties.

Following are some examples of wood products and how they are used.

LEARNING BY DOING

Soil Rebirth

I dumped a load of wood chips in one of my pastures with the intention of spreading it out, but I never got to it. The cattle found it was a wonderful playground and worked my neat pile into a flat, uniform layer about 4 inches deep.

A couple of years later, after a three-month period with zero rain, I scooped up the chips to spread. Underneath, the soil was still quite moist and full of earthworms, while all around it the soil was dry and cracked.

Wood Chips

Often produced during the removal of unwanted urban trees, wood chips have recently been found to possess impressive soil-improvement properties.

BENEFITS

One example is their long-term protection of the soil surface, which improves infiltration of rainfall and reduction in evaporation; this in turn improves soil moisture relationships. A surface layer of wood chips can also hold up to traffic, whether vehicle or animal, and thereby prevent soil compaction, which improves soil oxygen content.

Their physical size and nature makes them easy to spread either mechanically or by hand. At the same time, they are coarse enough that there is a relatively low amount of soil-to-wood interface that could result in nitrogen depletion of the soil, since wood has a very high ratio of carbon to nitrogen.

It is the decay process of wood chips, though, that may provide the best benefit. Because of their lignin content, they are broken down primarily by soil fungi, which provide substantial soil structure enhancement.

WAYS TO USE WOOD CHIPS

Avoid chips made from trees that are toxic to other plants, such as black walnut and red cedar. Also note that not all wood chips are the same. The wood from deciduous trees is different from that of conifers. The former is decayed by more desirable white rot fungi, as opposed to the coniferous chips, which are decayed by brown rot fungi.

Even within a species, the chips made from small branches and twigs are more nutritious than those from trunks, since the smaller-diameter branches have a higher percentage of living material and more nutrients for microbes, as opposed to just old cell wall material of cellulose and lignin. This smaller-

diameter wood is called ramial wood. Research has found impressive yield increases in garden crops mulched with ramial wood chips.

Because they decay so slowly, wood chips are a very long-lasting form of mulch. Leave them on the surface rather than incorporating them, to lessen any nitrogen depletion they may cause.

Sawdust, on the other hand, has a large amount of surface area and will definitely deplete soil nitrogen if incorporated into the soil. Typically, it is best composted with high-nitrogen materials. Wood chips, in contrast, usually have their best use when applied in a thin layer to the soil surface as a persistent, fungi-feeding mulch.

The use of wood chips in gardening has gained quite a cult following, popularized by a film featuring Paul Gautschi called *Back to Eden*, and it works quite well. Resources on this practice can be found on the internet under the search term "Back to Eden Gardening."

[Wood] chips made from small branches and twigs are more nutritious than those from trunks, since the smaller-diameter branches have a higher percentage of living material and more nutrients for microbes.

Waste Paper

Paper waste is basically the same thing as wood chips, sawdust, and logs but in a more processed form.

BENEFITS

When put on the soil, paper waste behaves similarly to sawdust. In addition, due to its flat nature (unless it's shredded) it can be used for many other purposes, such as a weed-control barrier. Layers of wet newspaper and cardboard are effective for smothering out weeds.

WAYS TO USE WASTE PAPER

Like other wood products, the carbon-to-nitrogen ratio of paper is very high, and the decay of paper will tie up nitrogen if incorporated into the soil. Using paper as a weed control fabric makes use of this "nitrogen tie-up" property, as many small seeded annual weeds such as pigweeds are obligate nitrate feeders, and a layer of paper can render the very top of the soil nitrogen deficient, while the lower layers can still be nitrogen rich. Desirable plants can be planted in slits cut through the paper.

"Lasagna gardening" is the name of a popularized technique that home gardeners can try, using paper and cardboard. You place a layer of paper or cardboard on the soil surface and top it with alternating layers of high-C:N materials and low-C:N materials to form a sort of sheet compost, and then you insert plants or seeds into slits cut in the paper. If earthworms are present, they will rapidly consume the paper, but only after it has done its job of suppressing weeds. Lasagna gardening is a great no-till method of converting a lawn into a garden, preserving the soil structure and root channels of the sod.

Hügelkultur

The practice of burying or partially burying large intact logs or pieces of logs, known as **Hügelkultur**, has been popularized by the books of Austrian farmer Sepp Holzer.

BENEFITS

Although initially labor intensive, Hügelkultur offers benefits that can be realized for a very long time and is a means of utilizing logs that are too large to run through a chipper and not useful for firewood or lumber, such as cottonwood.

Partially rotted wood is capable of holding tremendous amounts of moisture. The low surface area exposed to soil contact minimizes nitrogen tie-up (nitrogen being depleted due to the high carbon-to-nitrogen ratio of wood; see discussion of carbon-to-nitrogen ratio in Chapter 5).

WAYS TO USE HÜGELKULTUR

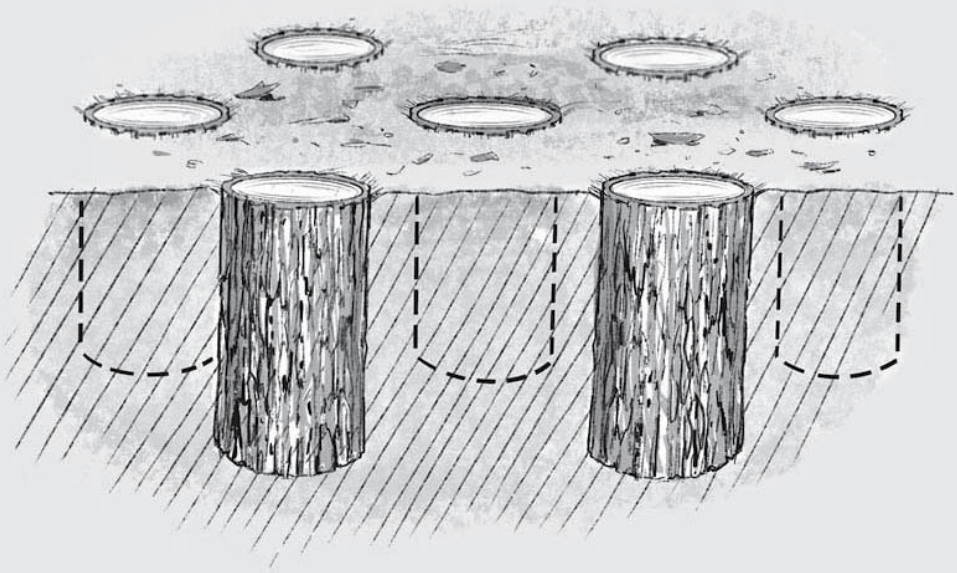
One way to use logs in a garden setting is to build raised Hügelkultur beds, in the shape of a prism or pyramid (see illustration). If oriented in an east-west direction, the south-facing slope has a warm microclimate, while the north-facing side has a cool microclimate, both of which can be put to use. The elevated nature of a Hügelkultur pile can also be used to minimize the need to bend over, much to the delight of those of us who suffer from sore backs.

A variation is to make a flat-topped raised bed with firewood-shaped logs placed vertically, to let plant roots grow deep between the logs. This also allows them to tap into the

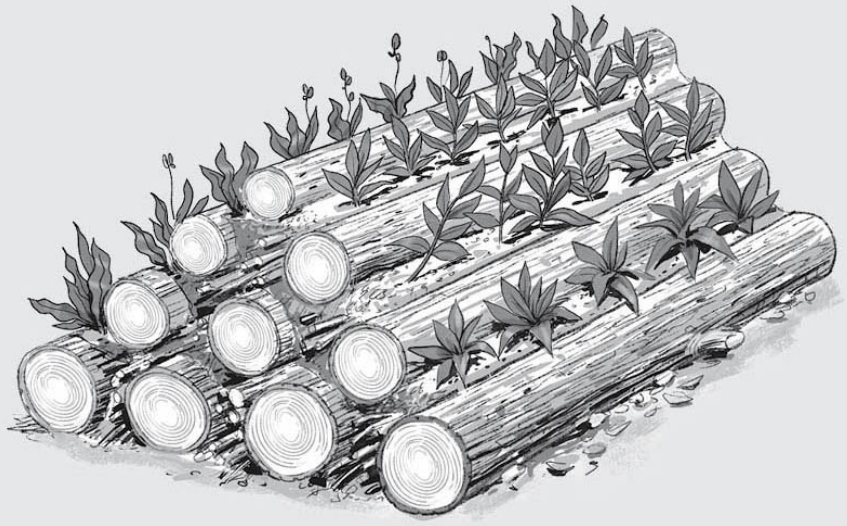
moisture held by the decaying logs. Another method is to simply place logs in a trench or other excavation. The logs can be fully or partially buried. If partially buried, logs can be placed on the contour of the slope to act like a terrace. Trees or other water-demanding vegetation can be placed next to this structure to utilize the retained additional moisture.

HÜGELKULTUR POSSIBILITIES

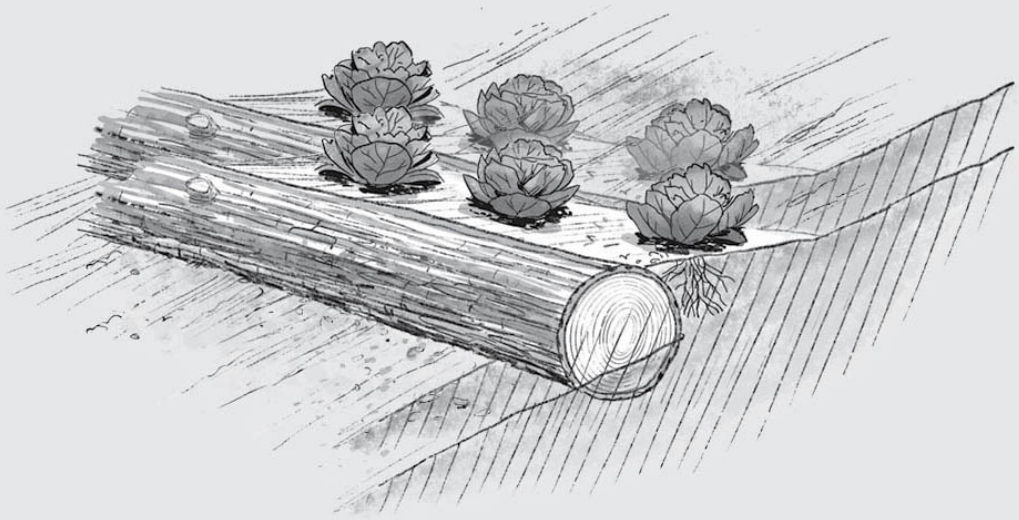
Hügelkultur, in either a buried trench or a raised bed, is ideal for dry climates with soil of poor water-holding capacity.



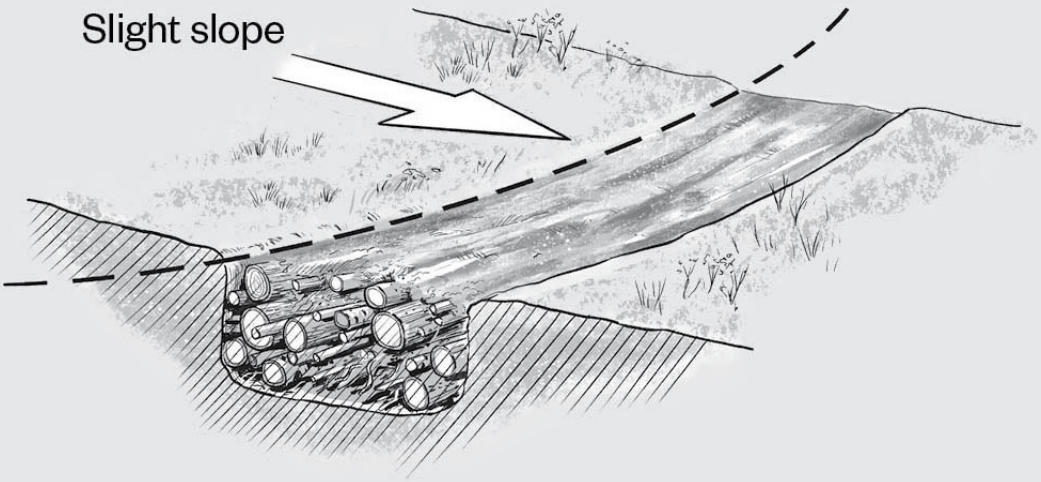
ABOVE: **Vertically buried logs** *can provide easy pathways for air and water to enter a dense clay soil.*



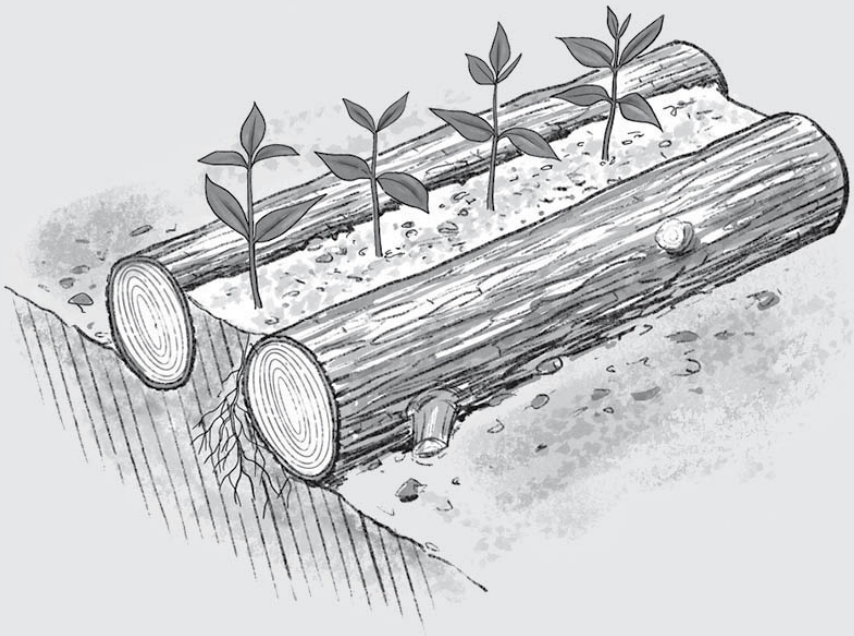
ABOVE: **In a pyramid raised bed**, *heat-saving plants face the equator; heat-sensitive plants face away from the equator.*



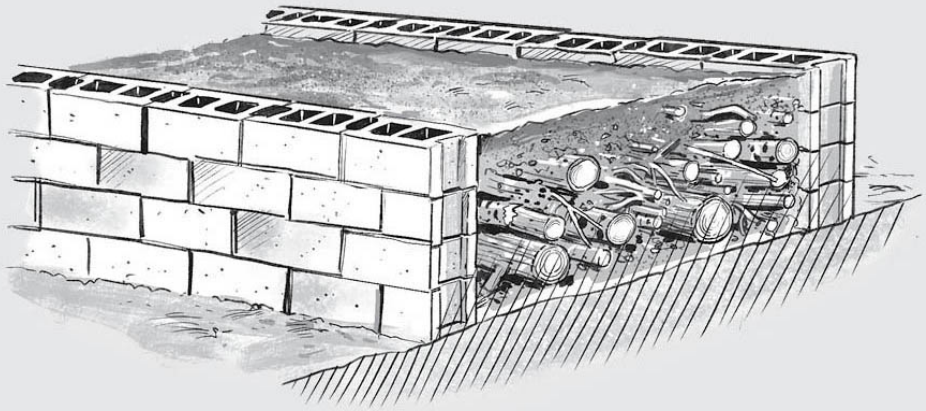
ABOVE: **A Hügelkultur terrace** *is useful for sloped areas.*



ABOVE: **A trench** *placed on the contour can capture runoff.*



ABOVE: **A twin-logs raised bed** *is ideal for areas with poor drainage.*



ABOVE: **A wood, stone, or concrete block wall** *can retain soil in a raised bed.*

Biochar

This substance is currently creating a great deal of excitement in the agriculture world, and rightfully so. First, it is charcoal, produced when once-living material is anaerobically burned within a certain temperature range designed to maximize its cation exchange capacity. Then this charcoal is infused with the three "M"s: moisture, mineral nutrients, and microbes. (See Figure 5.2.)

BENEFITS

In tropical soils, the results from applying biochar are simply astounding. In temperate soils, which generally have good cation exchange and water-holding capacity already, the results are less astonishing but still quite good.

One problem with biochar is that the amounts needed to make wholesale changes to soil are quite large, on the order of several hundred pounds per acre. It may be perfectly feasible, on the typical small farm common to most of the world (the world average is less than 10 acres, and about 70 percent of farmers have 2.5 acres or less), to generate biochar yourself and apply it to your acreage. In broad-scale agriculture, however, it is cost-prohibitive to apply enough purchased biochar at one application to impact soil significantly. But that doesn't mean that biochar does not have a role to play in large-scale farming.

THE TRUTH ABOUT TROPICAL SOILS

The story of biochar in the modern era is a fascinating tale, even to people who have no interest in making better soil to feed a starving planet. This treasure emerged during archaeological expeditions to find the legendary city of El Dorado in what became Colombia (see box). The legends stated that the city was not only loaded with gold but had a huge population as well. Until recently, scientists have claimed that this was impossible, because the very poor soils of the Amazon could not have produced enough food within travel distance to support a city of that size prior to motorized vehicles.

Indeed, the lush, dense growth of the Amazon jungle hides the fact that the soils themselves are extremely poor, with a miserably low capacity to hold and store either water or mineral nutrients. All the nutrients in the jungle are held in the plants themselves. The soils are quite unproductive, and it takes a large land area to produce food crops.

To sustain agriculture as we know it, the inevitable next step is to allow the jungle to reclaim and rejuvenate the now-degraded soil and then proceed to cut down and burn more forest. This process takes a lot of land area, because the area left to regrow trees must be several times the area actually being farmed. This is why historians have for centuries said El Dorado was an impossibility: the soils of the area could not support a city.

But early explorers found something potentially much more exciting than gold in the search for this city. They found pockets of rich black soils with an unusual ability to grow plants, a stark contrast to the bright red and infertile soils around them. Upon careful examination, these soils had

several characteristics in common: charcoal, animal bones, and evidence of human excrement.

These soils originated from the fecal waste, food waste, and charcoal left over from cooking fires, all mixed together. Whether this was an intentional plan to produce magically productive soil, or just a means of reducing the flies and odor inherent in human waste and food scraps, we may never know. But the result of this practice was a soil quite different from the surrounding soil.

El Dorado

El Dorado was a mythical city of gold, located somewhere in the Amazon rainforest and supposedly populated by the Muisca people. Natives told early Spanish explorers astounding tales of the wealth and treasures to be found there. Legend has it that each newly crowned king of El Dorado was covered in a coat of gold dust, laid on a raft and covered in gold and jewels, and then washed off in the nearby lake. The buildings were supposedly overlaid with gold and gleamed brightly in the sun.

Lured by these tales, countless treasure hunters over several centuries went on expeditions in search of this city and the riches within. All failed in their quest: some returned empty-handed and disappointed; others never returned at all. The latter group included the famous

explorer Percy Fawcett and the son of Sir Walter Raleigh (also named Walter).

Today people still believe that El Dorado actually existed, and they still search for it. A 2001 expedition found ancient maps in a monastery that hinted at the location of the city. A subsequent expedition to the location turned up hidden man-made tunnels and evidence of a secret, hidden civilization, but no gold. Attempts have been made to drain several lakes thought to be where the kings of El Dorado were cleansed of gold dust during their coronations.

THE TRUE TREASURE

While explorers have yet to find the city of gold, their quest has revealed a long-lost ancient practice, possibly invented by the people of El Dorado and developed throughout the region. This practice may be a hundred, a thousand, a million times more important than any El Dorado gold, which is, after all, just a shiny, malleable metal, with no intrinsic value. What recent Amazon explorers have discovered could cure world hunger and even prevent planetary disaster.

COMPARING CHARCOAL AND SOIL

The key to good soil, as described in earlier chapters, is to provide oxygen, mineral nutrients, and water to the same root at the same time. As a brief refresher, the ability to hold water

and nutrients derives from a characteristic of soil particles called cation exchange, the ability of soil to hold positively charged ions (called cations) to itself. Since most mineral nutrients required by plants exist as cations, and water also has one end of its molecule with a positive charge, the cation exchange capacity of a soil is also its relative ability to hold water and nutrients.

Tropical soils are derived from iron and aluminum oxide particles, which have very little cation exchange capacity, unlike the clays of temperate regions. These soils retain little water or fertility.

Charcoal, on the other hand, is full of pore space, and the carbon that makes up charcoal is very good at holding both positively and negatively charged mineral nutrients, as well as water. Charcoal also does not degrade over time as other organic substances do; it can last for thousands of years in the soil. The human wastes and food wastes that were also deposited with the charcoal supplied both mineral nutrients and an energy source for microbes, and all these combined made for an amazingly productive soil.

WAYS TO USE BIOCHAR

Here are two of the many ways to incorporate charcoal and biochar into your farm practices.

Add Charcoal to Your Livestock Feed

As mentioned, charcoal becomes biochar when infused with the three “M”s: moisture, minerals, and microbes. The easiest way to do that is to mix charcoal with manure, and the easiest

way to mix charcoal with manure is to feed the charcoal to animals and let the digestive tract do the mixing.

Consequently, the most profitable and environmentally beneficial use of biochar is to use charcoal as a feed ingredient for livestock. I know several ranchers who have put charcoal in the mineral supplement or feed ration for their livestock, and the results are impressive. One is Doug Pow, an Australian rancher famous for this "feed-through" method of biochar application (he is the subject of several YouTube videos and magazine articles).

As a feed additive, particularly for ruminants, charcoal has many benefits:

- **Charcoal absorbs and holds methane**, a dual benefit in itself. It prevents the methane in the rumen from entering the atmosphere, where it is a potent greenhouse gas. And it allows the methane to feed methanotrophic microbes in the rumen, which in turn become an energy source for the animal. The result is improved feed efficiency. One rancher I know claims he has seen a 17 percent improvement in feed efficiency after using charcoal as a feed supplement. Researchers also show a nice reduction in methane emissions after feeding charcoal to ruminants.
- **Charcoal absorbs many toxins** produced by molds, which are all too often found in feedstuffs such as corn, silage, and hay. Corn, for example, often contains aflatoxin, a poisonous compound produced by a mold that attacks grain damaged by such grain-feeding insects as corn earworm. This promotes animal health and well-being.

- **Biochar absorbs ammonia** in freshly deposited manure and prevents its volatilization to the atmosphere. At this stage the substance is considered biochar, since it contains moisture, microbes, and minerals. This prevents it from being an atmospheric pollutant while increasing the fertility value of the manure.
- **Biochar in the manure is buried in the soil profile**—the area where it is most effective—by dung-feeding animals such as earthworms and dung beetles, rather than left on the soil surface where it is of little value. Once in the soil profile, the biochar can work its magic: It retains moisture, harbors microbial life, and holds mineral nutrients in a form available to plants. With biochar, those nutrients are not easily lost to leaching or rendered less available by chemical processes in soil.

The amount of charcoal needed to achieve all of these benefits is quite small, about 3 ounces per 1,000-pound-animal daily (roughly 100 grams per 500 kg body weight). This is quite affordable, even if the charcoal is purchased.

Plant with Biochar

Another high-value way to utilize biochar is to apply relatively small amounts either on the seed or in the seed furrow, where it can make its impact during the critical germination period of the plant. When combined with biological inoculants such as compost extract, in which the biochar holds the moisture and

protects the microbes from desiccation, it can be quite effective in very small (and affordable) doses.

These small doses also add up over time, since biochar lasts thousands of years in the soil. Even 50 pounds per acre per year applied in furrow with seed at planting adds up to 500 pounds per acre over a decade, which is enough to have considerable influence on soil properties.

LEARNING BY DOING

A Biochar Mystery

The year 2012 saw the most severe drought most people in the Plains states can remember. One day that fall I called my brother. He was out picking corn on a little three-acre field he had recently expanded by bulldozing some trees along the edges.

I asked him how it was doing, and he said, “Terrible. Only about 30 bushels per acre. Sad thing is, this is one of my better fields this year.” Then he said, “Whoa. I think my yield monitor must be off, it just hit 240. And from the looks of the corn in this spot, it might be legitimate.”

I asked him what was different about that spot, and he didn’t know. But as we talked, every time he went through that spot, the yield monitor hit 240. Then it dawned on him: that was the spot where he burned and buried all the trees

he had bulldozed. It was buried charcoal that made the difference.

THE BEST WAY TO MAKE BIOCHAR

It is also important on a planetary scale to discuss the most beneficial way to make the charcoal. While using biochar is a great way to sequester carbon in the soil in a beneficial manner for thousands of years, when a tree is cut down and the wood is made into biochar, most of the carbon in the wood is put in the atmosphere with a fraction left remaining as biochar; in other words, we convert a large amount of stored carbon in wood into a small amount of "forever carbon" as charcoal. In the short term, biochar production creates more CO_2 added to the atmosphere, not less.

In my opinion, the best way to make charcoal is to source it as a by-product of woodburning for another purpose, whether that is electricity generation, or home heating, or home cooking, or some industrial process. Simply cutting down trees with already sequestered carbon in the form of wood and turning most of that carbon back into CO_2 during the charcoal-making process seems wasteful and counterproductive; making biochar from the burning of wood that is going to be burned anyway is smart.

On small landholdings, as exist in much of the tropics, a charcoal-producing stove (rather than an open fire for home heating and cooking) can produce enough charcoal for amending small amounts of land each year and to serve as a feed ingredient for a small flock or herd of ruminant animals

(the raw char or the manure containing the char can be used as a soil amendment).

Other Carbon-Based Soil Amendments

All materials derived from plant or animal origin can be used for fertilizer. They will contain the minerals plants need as well as energy for the soil microbes that decay them.

LAWN WASTE

Lawn wastes are valuable organic materials that are often just disposed of. If they can be acquired in quantity, they can be quite beneficial. The best places to obtain them are lawn care and tree care businesses, which often otherwise have to pay for their disposal. Lawn wastes can also be found near urban areas at city dumps and landfills, as well as through commercial lawn management businesses.

Fallen tree leaves have a fairly high C:N ratio. The flat shape of leaves creates problems with aeration, so grinding, blending with bulky materials, or frequent turning are needed to promote oxygenation during decay.

Lawn clippings are usually high in nitrogen, making the C:N ratio quite low. They can be alternated in layers with more carbonaceous materials such as fallen tree leaves to speed decay. Lawn wastes can be surprisingly high in nutrients and often contain considerably more nitrogen, phosphorus, and potassium (as well as trace minerals) than livestock manure.

SEAWEED

Seaweed usually refers to kelp but can include many other species as well. Seaweeds are rather low in actual nutrient analysis but contain many trace minerals and hormonal type compounds. They have been found to be beneficial in forms directly applied to soil, micronized and applied as a foliar spray, or as a compost feedstock. (See Figure 5.3.)

Different species of seaweed contain different compounds. Some are rich in auxins (which stimulate elongation of roots and shoots), while other species are rich in cytokinin (which stimulates branching and quantity of blooms). Fresh seaweed often is covered in salt, but this can be removed by simply rinsing.

Seaweed contains substances that improve soil aggregation. Kelp is also very beneficial as a livestock feed additive and is often used for this purpose, as it is reputed to reduce incidence of pink eye and foot rot in cattle, and similar ailments in other livestock. It stands to reason that manure from kelp-fed livestock will contain the same trace minerals that were originally in the kelp, to the benefit of both soil and livestock.

CRAB AND SHRIMP MEAL

Crab and shrimp meal are high in protein (and thus nitrogen and sulfur), as well as high in phosphorus, with analysis of 4-3-0. They are also high in chitin and promote growth of organisms that eat chitin, which may be beneficial for control of some pests, particularly root-feeding nematodes. Chitin also can trigger immune responses in plants, a phenomenon called systemic acquired immune response, which reduces many

plant diseases. Crab meal and shrimp meal decay rather slowly and are thus slow-release forms of N and P.

FISH BY-PRODUCTS

Fish meal, fish hydrolysate, and fish emulsion are all valuable organic fertilizers, being high in both nitrogen and phosphorus. Fish hydrolysate in particular seems to boost soil fungi, probably largely due to its high content of lipids. Fish by-products also have high value for livestock feed, especially for monogastrics, due to the high protein quality.

Because of their high value as livestock feed, fish by-products are usually too expensive to be used as a fertilizer source, but because they promote plant growth (beyond the effects of their nutrient content), fish by-products can be used profitably in many situations, such as with small amounts applied in furrow or in foliar applications.

It is thought that much of the benefit of fish by-products comes through stimulation of beneficial microbial products. Fish hydrolysate seems to be the best of these materials for stimulating plant growth, largely because the hydrolyzation process does not denature the proteins or ruin the value of the fish oils as microbial food; it is a very valuable plant-stimulating material but is also a very expensive material.

MAKE YOUR OWN FISH HYDROLYSATE

If you have access to waste fish products it is not difficult to make your own hydrolysate. This same process can be used to make a hydrolysate of any animal bodies.

1. Create a lactic acid starter using the method described here.
2. Grind up the fish or animal bodies to increase the exposed surface area.
3. Fill a container that can be made airtight (such as a 55-gallon plastic drum with a screw-type bung cap) with a blend of 40 percent fish waste, 40 percent water, 10 percent molasses, and 10 percent *Lactobacillus* starter culture.
4. Cap the container with a fermentation lock (available at wine or beer making supply stores). Allow the mixture to ferment for 6 to 8 weeks.

Assessing and Using the Hydrolysate

Good product using this method will be brown in color, with a pH of 4 and a somewhat mild smell. Bad product will have a

strong offensive smell and be black, purple, or green in color.

Use small amounts as feed or fertilizer. A little goes a long way. A gallon per acre applied in furrow with seeds or as a foliar spray diluted 1:10 with water gives very good effects. Do not apply it undiluted as a foliar, as it can severely burn plant leaves.

MOLASSES

A by-product of sugar manufactured from both sugarcane (cane molasses) and sugar beets (beet molasses), molasses is often used for increasing the palatability of mixed feeds. As a soil amendment, it is used to feed soil microbes or microbes in compost. It is a common addition to compost teas and extracts to feed soil microbes. Molasses is also high in trace minerals.

BONE MEAL

Bone meal is a by-product of animal slaughterhouses. It was once commonly used for livestock feed but concerns about BSE and other prion diseases have led to limiting its use for that purpose. Bone meal is a good but slow-release source of calcium and phosphorus. “Meat and bone meal” is a similar product but contains more protein material (nitrogen and sulfur).

FOOD WASTE

Food waste is highly variable in analysis of mineral nutrients (high-protein foods contain more minerals than carbohydrate-

rich foods), but all forms contain the most important item for soil: biological energy. Composting food waste results in a homogenous, low-odor product that is easy to apply (once thoroughly composted, food waste will be dark and crumbly and smell like rich soil).

Vermicompost

Vermicompost is the feces of earthworms (casts), plus the bodies of any dead earthworms. It can greatly stimulate seed germination and early growth.

BENEFITS

Simply food waste that has been processed by letting earthworms eat it, vermicompost has several advantages. It has been thoroughly digested and is odor-free; it has great structural stability, due to the glues secreted by the earthworms; and it is full of beneficial microbes that were cultured inside the earthworm digestive system. Vermicomposting is a very fun way to make use of household food waste (and it's a great source for fishing worms, if that is a desirable outcome).

WAYS TO USE EARTHWORMS

Three species of earthworms are typically used for vermicomposting.

- The most common is called the red wiggler. These worms reproduce quickly and process waste very quickly.

- The second is *Eudrilus eugeniae*, an African earthworm. Like the red wiggler (*Eisenia fetida*), it grows very rapidly in warm environments such as greenhouses or heated basements. It cannot survive in places where there is a winter, so in temperate areas there is no chance of its escaping and becoming a pest.
- Finally, there is the nightcrawler (*Lumbricus terrestrius*), a species that is slow to reproduce and slow to process food waste. They must be kept at temperatures around 50°F (10°C) and are killed by warm temperatures, like those found in a house. An unheated basement or root cellar is a good place to raise nightcrawlers.

Additional Virtues of Nightcrawlers

One benefit of nightcrawlers is that they can be sold for fish bait. Another is that this species of earthworm ingests soil along with food wastes. This means that the castings (fecal material) they leave are an intimate blend of humic substances, soil particles, and microbes that digest both organic and inorganic materials.

VERMICOMPOST EXTRACT

The major beneficial use of vermicompost is in making compost extracts, to create a liquid that is rich in microbes and is easily applied onto soil or seeds. There has been an entire science developed around vermicomposting. The basic process is simple.

1. Place bedding material (such as shredded leaves or shredded newspapers) in a container with holes in the bottom to allow for water drainage. Also include a lid that allows air to get in the container but keeps the worms from crawling out.

2. Moisten the bedding thoroughly and allow it to drain. Add the worms, then add food on top of the bedding and cover it with a very thin layer of more bedding. Do not add too much food at a time; earthworms need high levels of soil oxygen, and if the food rots, the microbes can use up all the oxygen. Put the lid on the container.

3. For red wigglers, the species most suited for household food waste, place the worms in a location where the temperature is between 50° and 80°F (10° and 27°C) and protected from sunlight.

4. Let the worms do their thing until the bedding becomes more worm casts than bedding. Then dump the

container out on a tarp, sort the worms from the used bedding, place new bedding in the container, add more food, and start anew!

A good worm bed container is made with two plastic tote containers, one placed inside the other, with small drainage holes (covered with screen) in the bottom of the top container; the bottom container collects drainage water. A flexible hose can be placed through a hole in the bottom container to channel leachate (extract) from the vermicompost to use as a seed treatment.

To prove the almost magical value of vermicompost leachate in stimulating seed germination, place an avocado pit in a worm bed. Avocados are notoriously hard to sprout, but place them in a worm bed and within a few months they will almost always be producing roots. These seeds can then be transplanted into pots.

Can Soil Make Its Own Fertilizer?

I am sure the mere title of this section is certain to raise a few eyebrows and elicit either anger or scoffing from the folks we often refer to as “conventional agriculture.” There are an awful lot of people who make a living selling fertilizer, and at one time I was one of them, and I am far from ashamed of that fact.

Despite the common perception that synthetic fertilizer is an evil substance, the fact remains that if no fertilizer were used in our current agriculture system there would be so little food produced that likely a good portion of the world would starve, and many more would be killed in fighting over what little food there would be.

As discussed before, someday we will run out of the raw materials for synthetic fertilizer. What then is the "Plan B"? The sooner we learn to obtain the mineral fertility essential for life without the use of mined fertilizers, the safer our futures are going to be.

Some organic farmers will tell us that they do not use fertilizers. Although they may not use synthetic fertilizers, they do quite often use applications of plant-based or animal-based materials as a source of mineral nutrients, such as using bone meal for phosphate or kelp meal for potassium.

It must be realized that these materials are simply moving minerals from an external source, like playing musical chairs. Those minerals had to come from somewhere originally.

With all this in mind, the goal is not about replacing synthetic fertilizers with an organic fertilizer; it is about not using fertilizer at all. How can we possibly feed the 9 billion humans predicted to be on Earth in 2050 after the fertilizer mines run out, when we can barely feed the current 6 billion humans now with the aid of fertilizer? Luckily, this may not be as impossible a task as it may seem.

Growing without Fertilizer

I heard a talk given by a prominent soil scientist who proclaimed that every soil has enough fertility to sustain crops for hundreds of years without fertilizer applications, if only we could make that fertility locked up in rock particles available to our plants. I thought to myself, she must be telling the crowd what they want to hear, rather than the cold, hard truth: that if you don't fertilize, you don't raise much. After all, I had seen with my own eyes what happened when I failed to fertilize, and that was miserable meager crops. But since I had too much respect for this scientist to simply discount what she was saying, I decided to investigate her claims.

I recalled a visit to the magnificent redwood forest of Northern California. There were 300-foot-tall trees growing out of what appeared to be nothing more than a thin layer of soil covering granite boulders. No one had fertilized this soil, ever. And yet there was plant growth far superior to any I had seen in my life. But it could be argued that this was a "closed" ecosystem, with no export of nutrients like there is in cropland. Maybe this "no fertilizer" concept could work in an environment where all nutrients are recycled back to the soil, and no material is removed—but it would surely crash if anything was removed.

The goal is not about replacing synthetic fertilizers with an organic fertilizer; it is about not using fertilizer at all.

Ocean Farming

GREENWAVE

Oceanic aquaculture has been touted as a way to greatly add to the earth's food supply. After all, the oceans make up 70 percent of the world's surface area, so why not use that area to grow food? Traditional fishing for food consists of harvesting what nature grows, but aquaculture involves the intentional growing and management of aquatic species.

Unfortunately, most aquaculture practices are nothing more than floating feedlots. Fish are housed in floating cages, cramped together in close quarters, and fed a prepared diet, often composed largely of soybean meal grown far inland and transported to the coast. Because of the crowding, disease is a hazard. The fish feces are concentrated in small areas and can contribute to pollution, mainly of excess nitrogen and phosphorus. Most of these nutrients will not return back to land and cause some serious issues, such as hypoxia, when they contribute to algal blooms.

In other words, traditional cage fish aquaculture transfers nutrients and carbon from land to sea, makes water pollution worse, and does nothing to combat climate change.

Farming Seaweed

A different approach to oceanic aquaculture has been developed by lifelong fisherman turned ocean farmer Bren Smith. Bren focuses on the culture of very rapid-growing aquatic plants like kelp, that take nitrogen, phosphorus, and carbon dioxide out of the water. In other words, kelp does the exact opposite of caged fish culture.

Seaweeds have many uses. Kelp has long been used as a livestock feed supplement, because it is rich in many minerals such as iodine that are often deficient in diets of animals grazing far inland. It is reputed to reduce pink eye and foot rot, two of the worst health issues of pastured cattle. Another species, *Asparagopsis*, has been found to reduce the methane emissions of cattle by a whopping 60 percent when fed at mere ounces per animal per day. Other species, such as the aptly named sugar kelp, are being promoted as human food (I personally love kelp).

Bren started the nonprofit GreenWave to train and support regenerative ocean farmers to grow kelp for food, fertilizer, animal feed, and plastic alternatives. In human food kelp is a low-carb alternative to noodles and pastas and can be an additive to many foods. There are many species of seaweed in addition to kelp, each of which has its own unique flavor and nutritional profile.

Farming Shellfish

In addition to the seaweed, the GreenWave model can also grow mussels, scallops, and oysters, which are filter feeders and function to cleanse the water, making them quite valuable in areas such as the mouths of rivers.

These shellfish also have another vital benefit. Their shells are made of calcium carbonate, a form of solidified carbon. The shells form by taking carbon dioxide out of the water, and once in the shell that carbon dioxide is locked away, sometimes for centuries. The shells can also be finely ground up and used for grit for poultry and are a valuable calcium source for egg-laying birds.

Between the shellfish and kelp, a farm such as this can take a very large amount of dissolved carbon dioxide out of the water.

Beneficial to Wild Fish

Another benefit of seaweed farming is that it increases wild fish populations, because it creates excellent habitat and provides a food source for aquatic organisms that are at the bottom of the food pyramid for wild fish. These wild fish can then be sustainably harvested as a fortunate by-product of the seaweed farming.

The kelp is grown on long ropes, while the mussels are grown in long “socks,” the scallops in lantern nets, and the oysters in small cages on the bottom. All are on the end of long ropes to facilitate harvest. The small fry of wild fish can obtain shelter between the mussel shells in the socks and the scallops in the lantern nets, another way that this

system aids wild fish populations. Bren remarks that the best sport fishing in the area is around his farm.

Beneficial to the Environment

Ocean farming has potential for tremendous environmental benefits if scaled up. It requires no inputs in the form of fertilizer, herbicides, insecticides, or any of the like. The amount of dissolved carbon dioxide removed from the ocean could be immense, whether through photosynthesis in the seaweed or sequestered into shells.

Excess nitrogen and phosphorus in water could be absorbed and formed into seaweed, and these nutrients transported back inland as human food or animal food, enriching the land while it cleans the oceans. In other words, ocean farming can help close the “poop loop” discussed in Chapter 6, in which water-based sewage systems literally flush out to sea millions of pounds of phosphorus escaping from mined deposits that are finite and rapidly being used up.

Seaweed could be used to reduce methane emissions from ruminant livestock, which would reduce the contributions of greenhouse gases, improve livestock feed efficiency and weight gain, and at the same time supply essential minerals such as iodine to the animals.

A mature 10-acre ocean farm in a year’s time can produce 50,000 pounds of seaweed and 250,000 shellfish; that is a lot of food and a lot of carbon dioxide, nitrogen, and phosphorus taken out of the ocean. Ocean farming is

labor intensive, but that should be viewed as a positive, because "labor intensive" is another term for "high job potential." It could potentially put millions of people to work in an industry highly beneficial to society and the planet.

It is also an industry with a relatively low need for capital investment, so these benefits can be realized even among the less privileged members of society. Imagine the potential for both food and environmental benefit if ocean farming on GreenWave's model became widespread!

To learn more, see For Further Reference.

Why can these perennial ecosystems be so productive without *fertilizer, and our cropland productive only* with *fertilizer?*

THE MYSTERIOUS PRODUCTIVITY OF NATURAL ECOSYSTEMS

Then I thought about the native prairie hay meadows where I grew up in southeastern Kansas. They produced a yield of hay every year, without fertilizer, as they had every year since the Civil War, and they maintained the same yield despite all the hay (and the minerals it contained) being removed each year.

Everything I was taught in college seemed to indicate that this was not possible. Soil tests on these native hay meadows have Bray P1 tests of zero, indicating there is absolutely no available phosphorus on these soils.

The hay crop each and every year says otherwise. Why can these perennial ecosystems be so productive *without* fertilizer, and our cropland productive only *with* fertilizer—when the cropland is located on "much better soils"? After all, the only places where natural ecosystems still exist is where soils were "too poor" to plow.

Digging into the Data

Was the soil scientist right when she said that every soil has enough fertility to last for centuries, if we just knew how to unlock it? I dug deeper.

The solid portion of soil is mostly composed of tiny rock particles of various sizes (sand and silt) with some clay (partially decomposed rock particles) and a small amount (usually less than 5 percent) of humus. I looked up the analysis of several rocks for phosphate (the most common limiting mineral element in most soils, other than nitrogen, which can be obtained from the air) and found that granite contains 0.15 percent phosphate, basalt contains 0.35 percent, and shale 0.35 percent.

That doesn't sound like very much. But consider that a 3-feet-deep root zone, containing 12 million pounds of soil per acre, would contain 18,000 pounds of phosphate if composed of granite particles, and 45,000 if composed of shale or basalt particles. That is a lot of total phosphate.

Alfalfa hay is one of the most phosphorus-demanding crops, using 12 pounds of phosphate per ton. At an average yield of 5 tons per acre, that is 60 pounds of phosphate per year. That means we have to render available only one-third of

one percent of the total phosphate in the rock each year in order to feed an alfalfa crop.

In cropland, that is not taking place; in natural ecosystems, apparently it is. What is the difference?

Natural Ecosystems vs. Cropland

Mimicking how a natural system works is the key to unlocking the natural fertility of soil in cropland. Here are the primary differences (to my mind) between natural ecosystems and cropland.

PHOTOSYNTHESIS

In a natural ecosystem, photosynthesis occurs from spring thaw until fall freeze-up. In my area, this is from early March until mid-December, or about nine months. In cropland, photosynthesis occurs from crop emergence until crop maturity.

In a corn crop planted on April 15, emerging on May 1, and reaching physiological maturity September 1, this is only four months, and the first month doesn't amount to much while the corn plants are small. This results in a significant difference in the amount of sugar produced from photosynthesis per acre, in favor of the natural ecosystem.

PLANT LIFE CYCLE

Natural ecosystems are dominated by perennial plants, while cropland is dominated by annuals. In order to perpetuate the

species, annuals allocate photosynthates toward seeds. Perennials survive the next year because the individual plants live through the next year, so photosynthates are sent toward the roots or stems so the plants can survive the winter. Part of the sugars sent to the roots are available to share with the soil ecology, and perennials send far more to the roots compared to annuals.

PLANT ROOT MASS

Perennials have huge root systems, while annuals have small root systems. The biomass of the root systems of several common plants are listed in the table below. This clearly shows that none of our crops even begin to rival native prairie grasses for root mass. The difference in root mass can also be visually demonstrated by a series of photos from the Land Institute in Salina, Kansas (see For Further Reference), comparing the root systems of annual wheat to that of perennial intermediate wheatgrass.

ROOT WEIGHTS OF VARIOUS PLANTS

CROP	POUNDS PER ACRE
Corn	3,000–4,000

SOURCE: G. C. Topp et al., "Changes in soil structure," in *Health of Our Soil: Toward Sustainable Agriculture in Canada*, ed. D. F. Acton and L. J. Gregorich (Ottowa, Ont: Centre for Land and Biological Resources, Research Branch, Agriculture and Agri-Food Canada, 1995), 51–60.

ROOT WEIGHTS OF VARIOUS PLANTS

Winter wheat	1,500–2,600
Red clover	2,200–2,600
Italian ryegrass	2,600–4,500
Native prairie grass	15,000–30,000

SOURCE: G. C. Topp et al., "Changes in soil structure," in *Health of Our Soil: Toward Sustainable Agriculture in Canada*, ed. D. F. Acton and L. J. Gregorich (Ottowa, Ont: Centre for Land and Biological Resources, Research Branch, Agriculture and Agri-Food Canada, 1995), 51–60.

MYCORRHIZAL FUNGI

Although MF are abundant in every natural ecosystem, they are conspicuously absent in cropland. They cannot survive for more than a few weeks without a live host plant. The conversion of natural ecosystems (dominated by perennial plants with live roots at all times) into cropland—featuring annual plants with root systems that die at maturity, followed by long periods of fallow—has resulted in mycorrhizal fungi being starved out of cropland. The surface area of mycorrhizal fungi hyphae on a colonized plant can be 1,000 times the surface area of the root hairs of an uncolonized plant.

FREE-LIVING LITHOTROPHS

Microbes that live in the soil and actually eat rocks (their name is Latin for "rock eating"), lithotrophs can act to break down

tiny rock particles and convert them into available minerals. These organisms derive energy from the oxidation of minerals in rocks and convert them into plant-available form.

Their bodies are based on carbon, however, so they need either carbon or carbon dioxide from decaying organic matter to build those bodies and reproduce. They require a constant source of that organic matter or root respiration in order to function, yet neither of these have been seen in cropland until, perhaps, recently, with the advent of continuous no-till farming combined with cover crops.

The mining industry uses these microbes to convert ores into metals, which are then extracted. But to my knowledge, virtually no one has put these microbes to use to unlock the fertility inside tiny soil particles and make it available to plants.

EARTHWORMS

Often prominent in natural ecosystems but rare in cropland, earthworms ingest soil particles and grind them in their gizzards, making a perfect home for lithotrophic microbes, which the earthworms move throughout the soil as they deposit their feces. As discussed in Chapter 5, earthworm feces contain more available nutrients than the surrounding soil. For more information on how to increase earthworm populations, see the discussion in Chapter 5.

LICHENS

A symbiotic relationship between lithotrophic fungi and a plant, which live together on the surface of rocks, results in a

lichen. (See Figure 5.6.) The plants provide the energy for the fungi, and the fungi dissolve the rock to make mineral nutrients available to the plant. While this is a commonly observed phenomenon in nature, to my knowledge no one has ever attempted to develop this symbiosis into a way to improve the availability of soil minerals in cropland. Lichens need undisturbed soil, which until the advent of no-till farming did not exist in cropland.

How Soils Get Addicted to Fertilizer

Root exudates feed microbial systems that naturally supply fertility, and high levels of water-soluble fertilizer shut this process down. If this high level, or overdose, continues for too long, it entirely depletes those microbial systems. The result is that most of our soils are incapable of producing good crop yields without fertilizer. In other words, they are addicted to fertilizer.

Obviously, if we are to restore soils back to a system where they can create their own fertility, then we need to stop applying water-soluble nitrogen and phosphorus fertilizers. The problem is that with our current "fertilizer-addicted" soils it will be difficult to maintain crop yields without fertilizer until these systems are restored.

For the rest of this chapter we'll discuss strategies for restoring natural fertility while still producing good crop

yields.

Repairing the Energy and Mineral Chains: A 5-Point Plan

Comparable to a food chain, the **mineral chain** in soil is a diagram that traces the movement of minerals from rock particles into plants and animals. Here's how it looks:

ROCKS → LITHOTROPHS → RHIZOSPHERE ORGANISMS → MYCORRHIZAL FUNGI → PLANTS → ANIMALS

The **energy chain** is a diagram of how energy and carbon flow toward the lithotrophs, for both cropland and a natural ecosystem. Here's how it looks:

PLANTS → MYCORRHIZAL FUNGI → RHIZOSPHERE ORGANISMS → LITHOTROPHS

In cropland, the mineral chain is not effective because the energy chain is defective. Annual plants with small root systems that lack mycorrhizal fungi, or growing in soil lacking earthworms, transfer very little energy to lithotrophic organisms. The way to make the mineral chain work and make more natural soil fertility available is to fix the energy chain, with the following measures:

1. EXTEND THE PERIOD OF PHOTOSYNTHESIS ON CROPLAND.

In most instances, this means planting cover crops when there is not a cash crop occupying the land. Without more photosynthesis, there will not be enough energy to make any of the following measures work. The energy produced by cover crops feeds soil ecology through roots when they are alive, and through decaying surface residue when they are dead.

If cropland is not in perennial vegetation, then cover crops should be grown any time there is not a cash crop with living roots. Root exudates are essential to transfer energy down the chain.

2. INOCULATE WITH MYCORRHIZAL FUNGI.

Most cropland does not have an effective population of these vital organisms because most cropland has had extended periods of fallow without live roots present, and the mycorrhizae have largely starved out. It may be possible to build the populations over time by cover cropping, but in my mind (I am not the most patient person) it makes much more sense to just use a commercial inoculant and start reaping the benefits immediately, then use cover crops to maintain the population.

3. KEEP A CONTINUOUS GROUND COVER AT ALL TIMES, WITH EITHER LIVE PLANTS OR PLANT RESIDUE.

If bare soil is not protected by ground cover, sunlight heats it enough to kill beneficial microbes, and ultraviolet light sterilizes the surface within minutes of exposure. Ground cover, in addition to blocking sunlight, promotes infiltration of rainfall and slows evaporation of soil moisture; this is critical because earthworms and most microbes need moist soil for optimal function.

Most species of earthworms and soil fauna function best when there is abundant plant residue on the soil surface, not buried within it. This residue should be of at least 7 percent protein content to feed earthworms.

One of the benefits of using cover crops is that they are typically killed in a vegetative state while still high in protein. Crop residues, on the other hand, are usually so low in protein that earthworms cannot use them as a nutritional source by themselves until fungi and bacteria have broken them down, in which case the earthworms actually eat the bacteria and fungi, not the crop residues themselves.

4. RECYCLE ORGANIC WASTES BACK TO THE LAND.

All organic wastes contain mineral fertility, but this is only part of the reason to apply them. They also provide the carbon and energy for lithotrophic microbes and earthworms.

Animal manure is the most obvious organic waste that should be returned to cropland, but sewage is also critical. This is increasingly true as the human population expands and as a higher percentage of that population lives where sewage is discharged into water bodies rather than returned to cropland.

Not only do organic wastes contain mineral nutrients in forms that are readily available to plants, but they can also feed earthworms and other lithotrophic organisms that make the nutrients in rock particles more available.

5. REINTRODUCE EARTHWORMS IF NONE ARE PRESENT.

You can always buy them from a bait store, but you will find this to be a mighty expensive means of soil improvement. A cheaper way is to collect them yourself in the early morning after a rain from known nightcrawler locations, such as most city lawns. You can also start with a few earthworms and raise them yourself in a pile of composting organic waste, then transfer the pile to your fields.

The red wiggler type worms used for vermicomposting do not do well in field conditions. They need a substrate of very high levels of organic materials, so they thrive in vermicomposting systems. Not that they are bad to apply, but they are quite different from nightcrawlers.

If proper habitat has not been established, introducing earthworms is a complete waste of time. Take all of the steps above before even thinking about introducing earthworms.

Rock Dust

There is a movement among some organic gardeners called “remineralization” that involves applying powdered rocks (rock dusts, usually of glacial or volcanic origin) to the soil. The

original proponent of using rock dust as fertilizer was Julius Hensel, author of the book *Bread from Stones*.

Rock dust is rather chemically inert, but if mixed with decaying organic matter it can be used to feed lithotrophs. The amount of actual fertility added by a rock dust application is usually insignificant, except at extreme rates. Even then it is so unavailable that it probably doesn't actually contribute much available fertility . . . *unless* it is applied in intimate contact with decaying organic matter or earthworms so that they build the populations of lithotrophic microbes. In turn, the microbes help to release the otherwise unavailable nutrients in the soil.

Cocomposting or vermicomposting rock dusts with organic wastes prior to soil application is likely to be far more beneficial than applying rock dusts alone to soil.

LEARNING BY DOING

Manure Magic

One of the first things I did when I bought my first farm was to **grid-sample** the farm. For those of you unfamiliar with this process, it involves taking multiple soil samples over an area and mapping areas according to soil test levels of various nutrients. One area of my farm was extremely deficient in phosphorus, where much of the topsoil had been removed to make a gravity irrigation system flow properly. The Bray P1 test was 7 ppm, which puts it in the extremely low category.

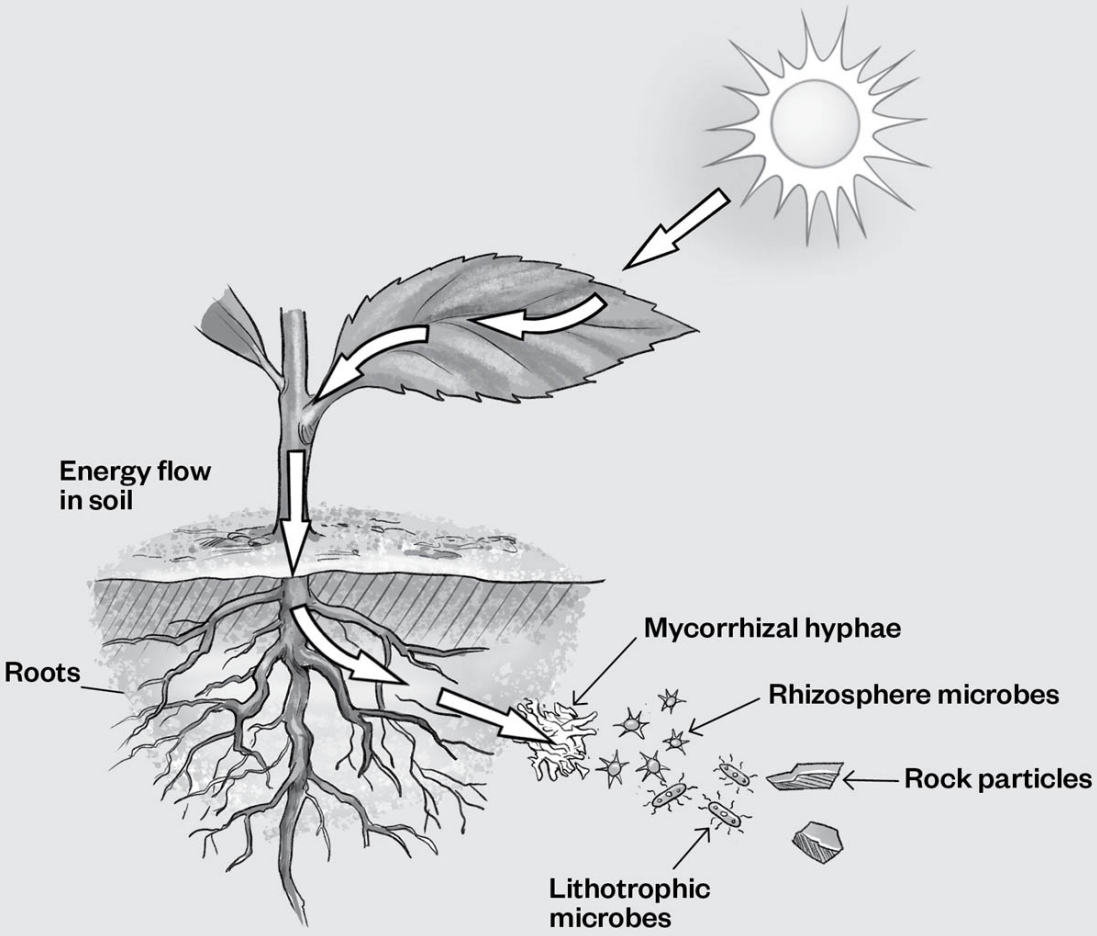
The winter after buying the farm, I chose to build up the soil fertility by feeding hay bales to my cow herd in the spot that had extremely low phosphorous. I probably fed a half-dozen 1,200-pound hay bales per acre, in that spot alone. Each bale of alfalfa hay contains about 8 pounds of phosphate. I was taught in college that it takes about 18 pounds of phosphate fertilizer to move the Bray soil test by 1 ppm. The next time I soil tested that spot, it tested at 115 ppm.

According to what I was taught in college, that soil test increase required 1,944 pounds of phosphate, or 3,738.5 pounds of 11-52-0 fertilizer. In reality, the increase was accomplished by feeding hay that contained about 48 pounds of phosphate. Where did the rest come from? There really isn't any other explanation except that the manure and rotted hay fed the biological system so that more of the fertility locked up in the soil became available. There is magic in manure. It has an effect on soil productivity far greater than what would be assumed just by looking at its mineral content.

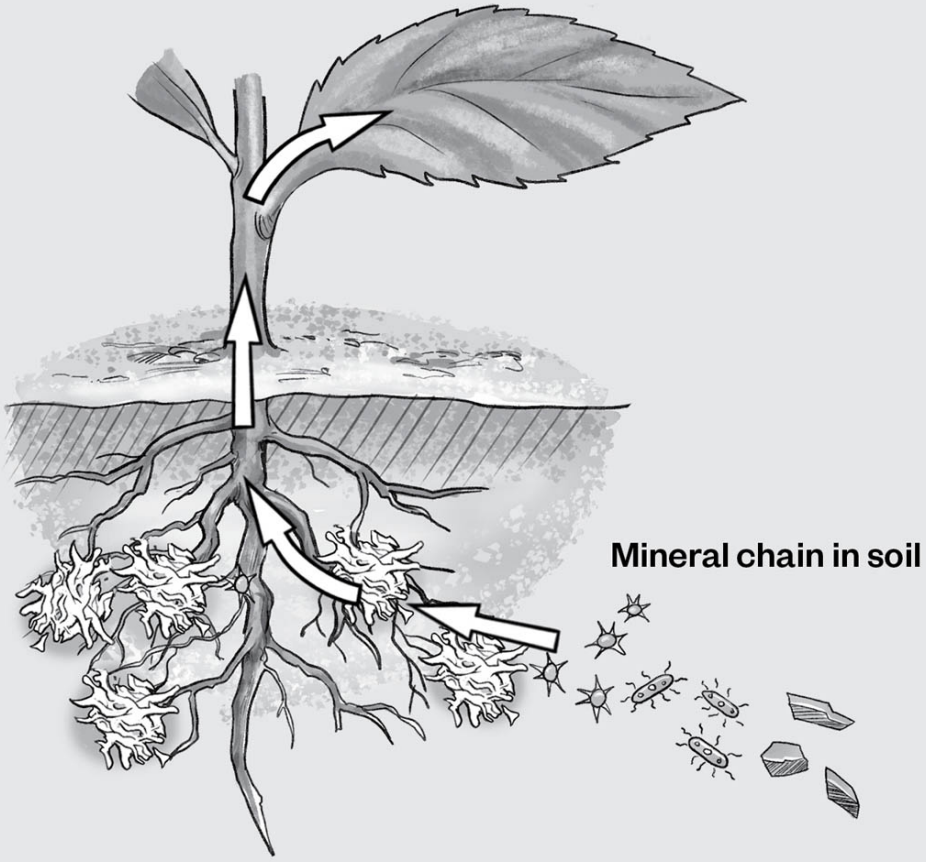
The easiest way to put manure on cropland is to graze animals in the field on crop residues or cover crops, or even grain crops, and to do all supplemental feeding on cropland rather than in confinement. Hauling feed is usually cheaper and easier than hauling manure because manure is wet and doesn't handle as well mechanically as grain or hay bales. In addition to manure and sewage, many other organic wastes are often available free for the

taking, particularly around urban areas. Wood chips, lawn clippings, restaurant wastes, and similar materials can all be put to use to good effect when applied back to land where they can feed soil biology.

ENERGY FLOW THROUGH SOIL



MINERAL FLOW IN SOIL



Rhizophagy: Plants May Be Vegetables, but They Aren’t Vegan

One very new and exciting discovery is a process called **rhizophagy**, which translates to "root eating." It is based on the finding that the tips of plant roots actually engulf bacteria and strip mineral nutrients out of them, then spit out the bacteria, and the bacteria go back to work obtaining nutrients. As we come to fully understand this process, we may be able to harness it and utilize a combination of lithotrophic microbes and a rhizophagous plant to extract mineral fertility from soil particles at a very efficient rate.

Going Forward

The next question you will have, after proceeding with the steps above, is likely to be, "What do I do now?" Well, I can boil your options down to three choices:

Keep fertilizing.

Stop fertilizing.

Do something in between fertilizing and not fertilizing.

This might seem like a no-win situation. If you keep fertilizing, you will always be locked into a system in which the natural mechanisms never develop, and you will always *have to* fertilize to maintain yields. The plants will never release those exudates and signaling compounds that trigger microbes to

dissolve rock particles, and eventually, when the mines run out, you will be in trouble.

If you quit fertilizing, practical experience indicates that crop yields will crash and you will suffer through years of poor economic returns. Furthermore, you'll have no idea of when the system will recover to the point at which fertilizing can be eliminated.

So, Fertilizer or Not?

Here is where my answer begins to get complicated. I would *not* recommend that you go "cold turkey" and just quit fertilizing. Why not?

First of all, it could be argued that since minable phosphate and potassium reserves are going to run out at some point, we might do our heirs a huge favor by hoarding as much fertility in our soils as we feel we can afford. It may someday be their best hope for survival in a mineral-hungry future world.

Second, all these processes designed to release minerals from rock particles are quite slow and unpredictable, and most of the processes designed to free minerals from rocks depend on maximizing photosynthesis (plant growth) as a first step. This may initially require fertilizer, preferably carbon-based fertilizers, since they also contain carbon and biological energy. Otherwise, you may not come close to releasing enough fertility to maintain optimal yields, and you won't know until it is too late.

Third, there just may be a compromise approach in which you can still utilize the convenience and proven performance

of fertilizers without shutting down natural processes that release natural fertility, while those systems are building. This can be combined with techniques proven over centuries that do not involve synthetic fertilizers. Some components of a compromise approach include the following. But first, make sure you have taken the steps above to fix the energy and mineral chains.

Going Against the Grain

Unfortunately, well-designed pastures and cutting-edge management are rare in pasture agriculture. Grazing management is all too often “turn them loose in spring and go discover them five months later”—on pastures consisting of whatever random plants have survived all the overgrazing and abuse to which they have been subjected for generations. These pastures not only generate little profit; they also offer limited benefit in the crop rotation, as they will contribute little nitrogen upon decay and will have far less soil biology than what they should.

Plant Perennial Pasture

Begin the program by planting a diverse perennial pasture, including healthy amounts of legumes, forbs with deep

taproots, and both cool-season and warm-season grasses for an extended period of photosynthesis. Use this mixture for pasture rather than hay, so that all minerals are recycled as manure rather than being removed from the area. Also, use a rapid rotational grazing system that maintains a tall residual stubble height on the forage when the animals are moved from a paddock, so that photosynthesis continues uninterrupted.

NITROGEN FROM LEGUMES

One of the primary reasons for taking this approach is to provide nitrogen from perennial legumes. Most annual legumes do not produce enough nitrogen in a crop rotation to fully replace all the nitrogen necessary for a highly productive crop of corn, cotton, or other nitrogen-demanding crop. However, it is entirely feasible for the needs of a such a crop to be met by the decay of a perennial legume-based pasture that has grown for several years.

This is not exactly new knowledge; it is how good crop yields were maintained for centuries prior to the advent of cheap nitrogen fertilizers resulting from widespread production of ammonia by the Haber-Bosch process. But it is a rarity today. We seem to think of cropland as too valuable to use as pastures, but a well-designed temporary pasture on good cropland with cutting-edge grazing management can often generate more profit than a good grain crop.

MINERALS FROM MANURE

The second benefit from a pasture is, of course, the cycling of mineral nutrients through manure. Once pastures in a crop

rotation are considered to be a way to build soil fertility and biology, the number of situations in which they can be used increases. For example, we think of pastures as being feed only for cattle and other ruminants, but swine and poultry can also be raised on pasture, and forage can constitute a fair percentage of their diet. While pastures are not good energy sources for monogastric animals, they are good sources of vitamins, minerals, and protein, which just happen to be the most expensive parts of the ration. Raising monogastrics on pasture is a *very* rapid way to build soil fertility because most of the feed for these animals is in the form of grain that is imported onto the field.

ROOTS CREATE A COMMUNITY

But the biggest benefit of all in the long run may just be the large and continuous flow of diverse root exudates from the huge root systems of a polyculture of perennial plants from several different plant families. While most people may think a pasture is just for herbaceous plants, incorporating trees for shade or the production of edible foliage or fruits can also greatly add to the diversity of root systems, root exudates, and associated microbes.

For example, pine trees planted for windbreaks (to shelter livestock in winter) and oak trees planted for acorn production (to feed monogastric livestock in fall) can harbor ectomycorrhizal fungi, which are different from the endomycorrhizal fungi harbored by herbaceous plants. Ectomycorrhizal fungi have a much stronger ability to bore into rocks to extract nutrients than endomycorrhizal fungi.

This explains why many rocky areas with poor soil are often populated with oaks and pines. Combining these species in a pasture can increase the ability of the entire vegetative community to utilize nutrients from rock particles, as leaves and fruit drop from the trees and are consumed by either livestock or soil organisms to be released and consumed again by other plants.

The drawback of including trees in a pasture mix is that rotating to a grain crop after a few years is not nearly as easy. That doesn't mean that the idea doesn't have merit, and it may be exactly what is needed for some areas of shallow, rocky soil. But instead of being in place for a mere four or five years, our pasture may need to remain in place for several decades, after which that shallow, rocky soil just might have become deep and fertile.

First, perform both traditional and routine soil tests, and apply fertilizer accordingly to most of your field. Then, on the remainder of your field, conduct comparison strips with both increased and reduced amounts of fertilizer relative to the recommended rates, and measure the yield.

Determine Fertilizer Need

I would encourage a careful monitoring program based on soil testing, starting with a traditional soil test followed by a Haney

test. The traditional test will measure nutrients made available by chemical extractions meant to mimic roots. The Haney test is designed to predict nutrient release from organic compounds upon decay. Together, they should be a very useful guide. However, no laboratory soil test will ever exactly duplicate what a plant root can, nor can it accurately predict what your true fertility needs will be.

The best feedback will come from following this simple but important procedure: First, perform both traditional and routine soil tests, and apply fertilizer accordingly to most of your field. Then, on the remainder of your field, conduct comparison strips with both increased and reduced amounts of fertilizer relative to the recommended rates, and measure the yield. If reduced rates of fertilizer do not reduce your yield compared to recommended or increased amounts, then your program is taking effect.

This may seem cumbersome, but it is exactly how traditional soil test recommendations were originally derived: measuring a certain number of ppm from a Bray extract of a test plot and applying increasing amounts of fertility to multiple strips until yields plateau. The amount of fertilizer needed to make yields plateau at that soil test level became the recommendation, at least for the yield levels of that growing season.

Repeat this over a number of years and you get some idea of how to make a good prediction of the amount of supplemental fertility you need, based on how many ppm Bray extract (or Olsen or Mehlich extracts) your soil released upon extraction.

Avoid Water-Soluble Fertilizers

When fertilizer is needed, try to use a source that does not contain water-soluble nutrients. This runs counter to conventional fertilizer advice, but if the goal is to build a system that creates its own fertility, then water-soluble fertilizers are going to hinder that goal by reducing root exudates and plant signaling compounds.

Examples of fertilizer sources that are not water-soluble include blood meal, feather meal, and fish hydrolysate for nitrogen; bone meal or colloidal rock phosphate for phosphorus; and kelp meal or rock dust for potassium. Well-composted manure will usually have low water-soluble fertility levels, but high levels of total fertility. Raw manure, especially uncomposted poultry manure and hog manure in slurry form, will often have high levels of water-soluble nitrogen.

Conventional wisdom says that a fertilizer with poor water solubility is not going to be very plant-available, with rock phosphate being a prime example. Rock phosphate has a total of about 30 percent phosphate, but virtually none of it is water-soluble, and only about 10 percent of that phosphate is considered available in a citrate solution (used in soil testing to mimic root availability) so rock phosphate will typically have an official fertilizer analysis of 0-3-0 which sounds pretty miserable.

In a system with very poor biology, rock phosphate will certainly give poor results compared to the acidulated fertilizers we buy commercially. But here is the rub: The longer a water-soluble phosphate fertilizer sits in the soil, the less available it becomes, as it is converted into unavailable forms

by iron, aluminum, calcium, and clay. By contrast, the longer rock phosphate sits in the soil, the *more available* it becomes through biological action. And it is precisely this biological action we wish to stimulate.

Use Carbon-Based Fertilizer

Any fertilizer source that is derived from a plant or animal product will contain carbon in addition to its fertility, and this carbon provides energy for microbes in addition to mineral nutrients. In general, the more active the microbial population, the more effective the natural systems that release minerals from rocks will become. Composts, manure, blood meal, bone meal, fish meal, liquid fish, crab meal, leaf mold, lawn clippings, and anything derived from a plant or animal origin should supply biological energy in addition to nutrients.

CHANGING SYNTHETIC FERTILIZER INTO CARBON-BASED FERTILIZER

If carbon-based fertilizer sources are not available or are prohibitively expensive, in some cases it is possible to apply synthetic fertilizers in a manner that does not interfere with the production of root exudates and signaling compounds.

Nitrogen fertilizers. One way to do this is to apply a high-energy carbon source, such as molasses, in conjunction with water-soluble nitrogen fertilizers. The sugar in the molasses is used as an energy source for bacteria, which rapidly multiply

and absorb the nitrogen and combine it with the carbon from the sugar to form protein in their bodies. This protein gets slowly recycled back into plant-available nitrogen as the bacteria are consumed and excreted by soil organisms.

Adding a source of high-energy carbon is easiest when the fertilizer applied is in liquid form, so the energy source and fertilizer are easily well mixed. In addition to liquid molasses, forms of energy sources include liquid fish products, liquified kelp, and other liquified plant products.

Phosphate fertilizers. Water-soluble phosphate fertilizers can slow the signaling compounds that trigger mycorrhizal colonization. Adding humic acid, fulvic acid, or humates (also referred to as leonardite or lignite) can act to combine with the phosphate to form a complex in which the phosphorus is still available to plants, but the colonization of mycorrhizal fungi isn't reduced.

Phosphorus in this form is also less vulnerable to being converted into unavailable forms of phosphorus by excess iron, aluminum, or calcium ions in the soil (see the phosphorus section in Chapter 6). Again, adding an energy source such as molasses with phosphate fertilizer also helps sequester the phosphate into bacterial bodies just as it does nitrogen, keeping it in a biologically active form to be released upon digestion of the bacteria by their predators.

Mobile and Immobile Nutrients

Some nutrients are mobile in plants (N, P, K, Mg, Mo, and Cl) and can move throughout the plants from a foliar application to where the plant needs them. All other nutrients are rather immobile in plant tissues, because they are converted into structural compounds after being taken in by the plant and are no longer free to move around.

You may need to apply immobile nutrients more frequently, because as new leaf tissue emerges it is likely to be deficient.

FOLIAR FERTILIZERS INCREASE ROOT EXUDATES

Another trick to prevent fertilizer from reducing root exudates is to apply it in a foliar application. If a leaf is nutrient deficient, it will not photosynthesize well, and if there is poor photosynthesis, there will be poor production of root exudates to feed microbes. An application of foliar fertilizer absorbed directly by the leaf can remedy the deficiency and increase photosynthesis, which increases the production of root exudates. Therefore, foliar-applied fertilizers can increase root exudates rather than decrease them.

Foliar applications can also bypass undesirable chemical reactions in the soil that render them unavailable. A good example of this is iron. Iron applied to an iron-deficient soil will almost certainly be converted into unavailable forms. But foliar-applied iron is immediately available for plant use and effective in even small quantities.

Always use foliar-applied nutrients along with a carbon source. This will reduce the leaf burn that can be an issue with this type of fertilizer.

Iron applied to an iron-deficient soil will almost certainly be converted into unavailable forms. But foliar-applied iron is immediately available for plant use and effective in even small quantities.

TIPS ON USING FOLIAR APPLICATIONS

The ability of leaves to absorb a quantity of nutrients at a time has been considered quite limited, and therefore foliar applications have found most use with micronutrients, which are effective even in small concentrations. They have been used very little for the macronutrients, such as nitrogen, that are needed in large quantities. But this may be changing as we learn more.

There are ways to safely and effectively apply even large amounts of urea through foliar applications. One key is to use urea dissolved in water, rather than the typical liquid urea-ammonium-nitrate combination, which causes severe leaf burn. As with other foliar fertilizers, don't forget the carbon source; in this case it doesn't feed soil microbes so much as it increases the rate of fertilizer uptake through the leaf.

By using all these procedures, over time you should be able to build a sustainable system that extracts minerals from rocks, and your dependence on external fertilizer inputs should decrease a little more each and every year. In addition,

your knowledge of this system will increase, and you will understand what you can and cannot achieve on your own soils over time.

Using Foliar Nitrogen on Pasture

One very beneficial use of foliar-applied nitrogen is on pastures with mixtures of grasses and legumes. Because legumes in a grass-legume mixture share only a limited amount of nitrogen with the neighboring grasses, the grasses in that mix are often nitrogen deficient.

Applying a water-soluble nitrogen source to the soil would help the grass—but it would also suppress the fixation of free nitrogen by the bacteria on the legume roots. A foliar nitrogen application could help the grasses without depressing the production of nitrogen by the legumes.

CHAPTER 6 SUMMARY

- Soil pH is a measure of soil acidity; the pH level of the soil can greatly affect plant growth.
- Soils that are too acid can negatively affect soil microbes and proper nutrient cycling; acid soils can be remedied through applications of liming materials such as finely ground limestone.
- Soils that are too alkaline can negatively affect plant growth by reduced availability of many mineral nutrients; it is usually more economical to improve the availability of these nutrients than to make the soil more acidic.
- Nitrogen is the soil nutrient that is most commonly deficient in soils for optimal plant growth, so it is the most common mineral applied to soil as fertilizer.
- Phosphorus is the second most deficient nutrient in most soils. Phosphorus fertilizers are mostly produced by treating rocks containing a mineral called apatite with acid to make the phosphorus more available. These apatite-containing deposits are relatively rare throughout the world.
- Potassium is the third most commonly deficient mineral; it is usually applied in the form of potassium chloride or potassium sulfate, two common minerals found where ancient lakes or oceans evaporated.

- Sulfur, iron, zinc, boron, manganese, magnesium, nickel, silicon, calcium, copper, molybdenum, and chloride are all minerals that may be deficient in some soils; each has its own unique role within the plant and fertilizer strategy.
- Carbon-based fertilizers are fertilizer materials of biological origin that contain mineral nutrients. Examples include animal manure, sewage, composts, woody debris, paper, lawn wastes, seaweed, charcoal/biochar, and various by-products of food manufacture such as animal bones, feathers, hooves, hides and hair, shells of crab and shrimp, molasses, and vegetable wastes.
- There are tremendous amounts of most minerals necessary for plant growth in almost every soil, but they are locked inside soil particles and completely unavailable to plants. Strategies to improve the availability of the minerals in these soils may be critical to feeding the world population in the future.

07

Carbon Cycle and Energy Flow

During photosynthesis, the energy captured in plant leaves combines carbon dioxide and water to form glucose (simple sugar) and oxygen. Every organism in every ecosystem derives its energy from this process, either because it is a plant, or it eats plants, or it eats something that eats plants, or it eats something that eats something that eats plants, or . . . you get the picture.

Carbon Is Life

Carbon, which originates as glucose from plant photosynthesis, is the currency for all biological systems (outside of a few chemotrophic organisms around volcanic vents, if you want to be really picky about it).

The amount of energy in a biological system is limited by the amount of glucose that is produced by photosynthesis in that system or that is transferred from another system. For example, the aquatic systems around mouths of rivers are often unusually productive because of the organic materials that wash down the river, materials that were produced upstream.

The Role of Root Exudates

We have known for a long time that plant production feeds ecosystems. This is visibly apparent as we harvest crops and see

animals graze. But a relatively recent revelation is that a remarkably high percentage of the photosynthetic products in a plant, from 25 to 50 percent, are excreted from the roots as root exudates. What possible advantage does this apparent charity offer the plant? Evidently, that energy given so freely to the soil system must be doing something for the plant because some of our most successful plants in cultivation are among the most generous plants with their root exudates.

Another recent discovery is just how much more important these root exudates are to building soil organic matter than the decay of the plant material itself. The table at right shows just how much more roots and root exudates contribute to soil organic matter than the visible aboveground plant material. Obviously, root exudates and the soil organisms that feed on them are a prime driver in soil building, which is why a cover crop is capable of improving soil organic matter even if it produces a limited amount of aboveground biomass; it is the amount and duration of root exudates that really count.

Increasing Photosynthesis

But all those root exudates are not produced if there is no photosynthesis occurring. The key to increasing productivity of our agroecosystems is to increase the amount of photosynthesis per unit of land area. An added benefit that we often overlook (but one that we should never fail to point out) is that photosynthesis is a process that takes carbon dioxide out of the atmosphere and converts it into both food and soil organic matter. In other words, the process of photosynthesis

pulls CO_2 out of the atmosphere to combat potential climate change. At the same time, it makes more food available for humans and all other life on Earth, and it makes more soil organic matter that reduces the likelihood of both droughts and floods.

Obviously, we should strive to maximize photosynthesis on every acre we manage because there are so many benefits to all life on Earth. Conveniently, this is almost always the means to increasing profit from the acre as well! I love it when doing the right thing makes more money! To optimize photosynthesis, we must first understand how the photosynthetic process works. Then we must determine what factors are limiting the amount of photosynthesis occurring on an acre. Finally, we must work to eliminate those limiting factors.

WHICH PLANT PARTS CONTRIBUTE MORE TO SOIL ORGANIC MATTER?

Belowground (roots and root exudates)	46.0%
Aboveground (stems, leaves, fruits)	8.3%

Source: Average of multiple studies

THE CARBON CYCLE

All life on Earth is dependent on the carbon cycle. While atmospheric carbon dioxide is under scrutiny because of its role in potential climate change, the fact remains that carbon

dioxide is the foundation for all life on Earth. Without it, there is no life.

It is essential that we have carbon dioxide in the atmosphere, but as with so many other things, it is possible to have too much of a good thing. Carbon dioxide is a greenhouse gas, along with methane, water vapor, nitrous oxide, and a few other gases. This means these gasses have the ability to slow the escape of heat from the earth into the atmosphere.

This process, like carbon dioxide itself, is also critical to life on Earth. Without the "greenhouse effect," Earth would be much like Mars, experiencing huge swings in temperature between day and night, with day being unbearably hot and night being unbearably cold. The greenhouse effect acts to hold some of the day's heat near the surface to allow life to exist.

But there must be a balance. The amount of heat that leaves the earth must be exactly the same as the amount of heat that comes into the earth from sunlight, or the temperature of the earth will increase.

Carbon dioxide is the foundation for all life on Earth. Without it, there is no life.

How Do We Take These Steps?

One immediate change would be to stop the mass migration of carbon from soil to the atmosphere, due to soil tillage, by transitioning all the world's cropland to no-till farming, as described in Chapter 8. After all tillage is stopped, we then

need to begin increasing the carbon input into cropland soils, through wise crop rotation practices (Chapter 9) and the addition of cover crops to cropland systems (Chapter 10). The most effective way to rapidly increase soil carbon on cropland is to convert cropland to perennial grasslands and graze them with large herbivorous animals, even if only for a few years.

Existing rangelands and pastures also have potential to store much more carbon. Most of the world's pastures and rangelands are both understocked and overgrazed. Transitioning from traditional, continuous grazing to modern, adaptive managed multipaddock grazing systems could potentially increase carbon sequestration in rangelands by a significant factor while simultaneously increasing the production of meat, milk, and fiber from those areas and improving wildlife habitat and other ecosystem services.

Then, finally, we look at the world's forests and the potential to convert cropland to forests or combinations of grasslands and forests (savannas). Forests do not build soil carbon or accumulate biomass as effectively as grasslands, but after just a few years the aboveground biomass of grasslands reaches a peak and goes no higher. By contrast, forests (despite their slower growth rate) do not "plateau" in biomass after a few years and continue adding aboveground biomass for several decades. But growth rate and carbon sequestration of forests can also be accelerated through management as well, as described in Chapter 12.

PHASES OF THE CARBON CYCLE

It is easiest to understand the carbon cycle when it is broken down into several parts. As we do this, let's keep this challenge in mind: **There is too much carbon in the air, according to most atmospheric scientists, and too little carbon in soil, according to soil scientists.**

The amount of carbon dioxide in the earth's atmosphere has been rising for centuries now, at a rate not seen before in human existence. This has caused great alarm among many of the world's top scientists, since a change in the greenhouse effect could have catastrophic effects on the world's climate. The carbon cycle has a role in improving soil and improving the world's food supply, as well as in averting potential climate catastrophe.

Let's consider how we can manage the carbon cycle to take more out of the air and put more into the soil. As we look at the eight parts of the carbon cycle, let's see how each can be modified to reduce atmospheric carbon.

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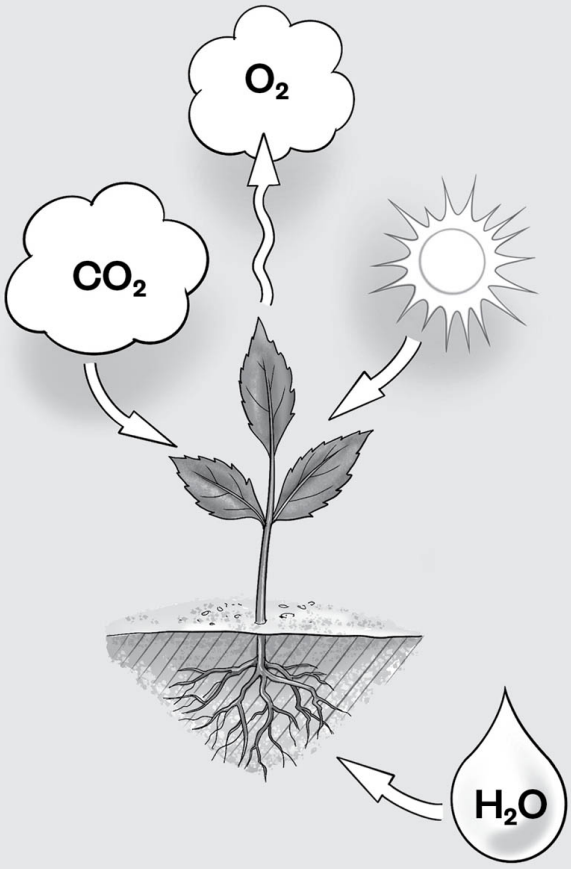
1. Photosynthesis. In photosynthesis, carbon dioxide from the air is combined with hydrogen from a water molecule, producing glucose and oxygen.

How we can help. The biggest single step that can be taken to reduce atmospheric carbon dioxide is to increase

the level of photosynthesis across the globe. That is exactly what the rest of this chapter is about.

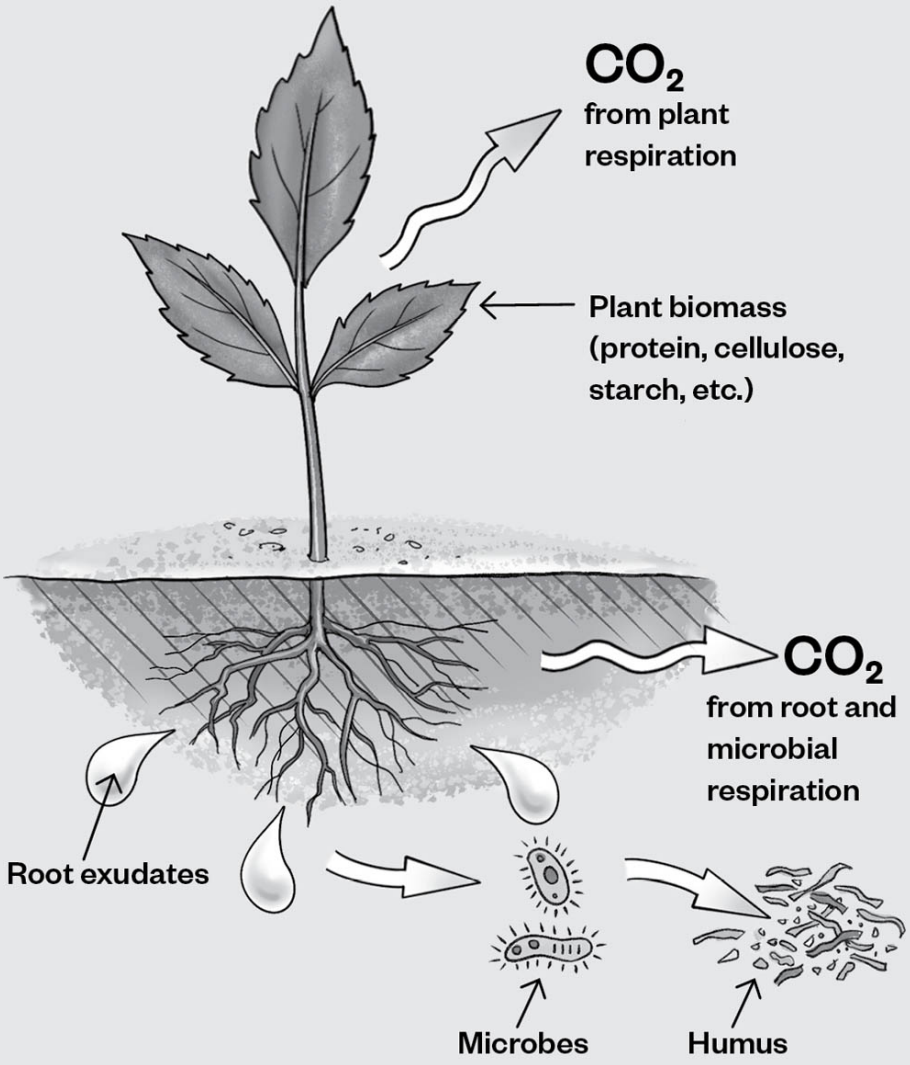


2. Glucose. The glucose in a plant has three potential pathways:

- It is used by the plant as an energy source (**respiration**) and converted back into carbon dioxide and water vapor.
- It is converted into carbon compounds (protein, cellulose, lignin, fats, starch, etc.) in the plant.

- It is exuded from the roots as root exudates, used by soil microbes in the rhizosphere. These microbes are the primary source of long-lived soil carbon compounds, collectively called soil humus.

How we can help. Increasing root exudates is probably the single best step to improving soil carbon storage. This will be discussed primarily in Chapters 10 and 11. To understand the importance of root exudates on soil humus, see the table.

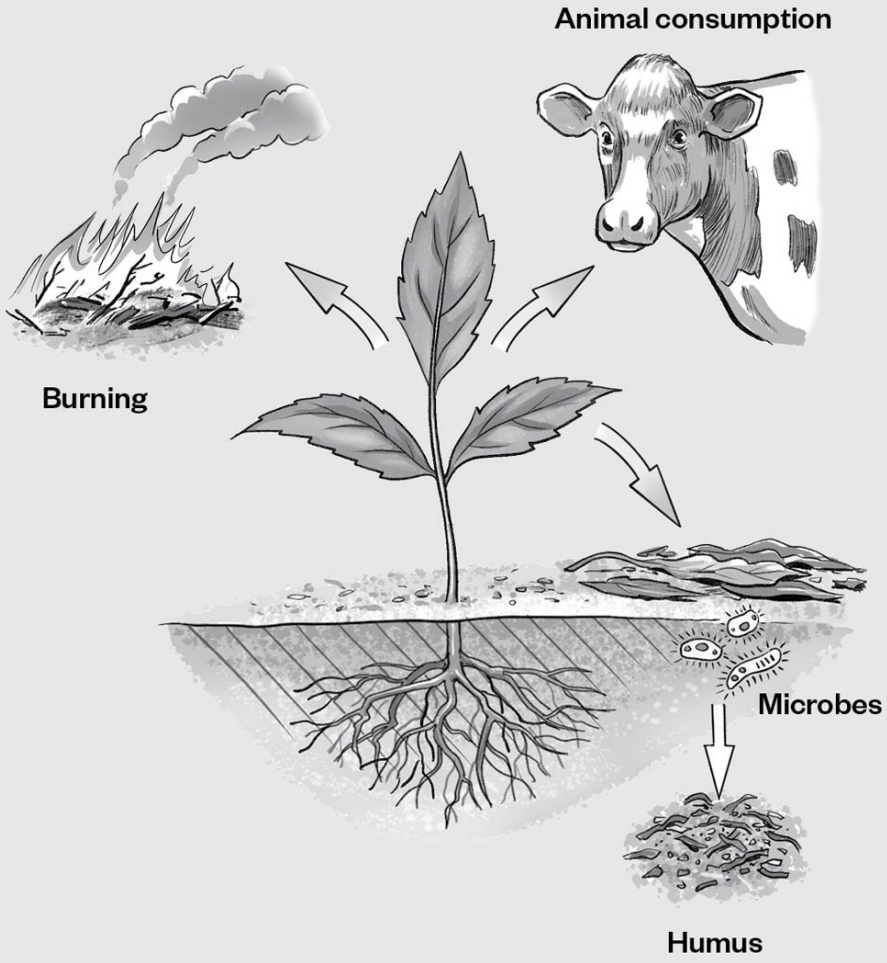


3. Biomass. The compounds in the plant have two eventual fates: Either the plant is consumed (by an animal, or by microbes during decay) or it is burned.

- If it is burned, almost all of the carbon is quickly returned back to the atmosphere as carbon dioxide. If the burning occurs where oxygen is limited, some of the carbon is retained as charcoal (see Other Carbon-Based Soil Amendments).

- If the plant is consumed by an animal or microbe, part of the carbon is retained in the body of the consuming organism; some is used in respiration and returned to the atmosphere; and some is excreted as manure or the microbial equivalent of manure. The microbial equivalent of manure becomes long-term soil carbon compounds, or humus.

How we can help. The conversion of plant carbon into long-lived soil carbon is most effective when processed in the body of a ruminant animal, as discussed in Chapter 5.

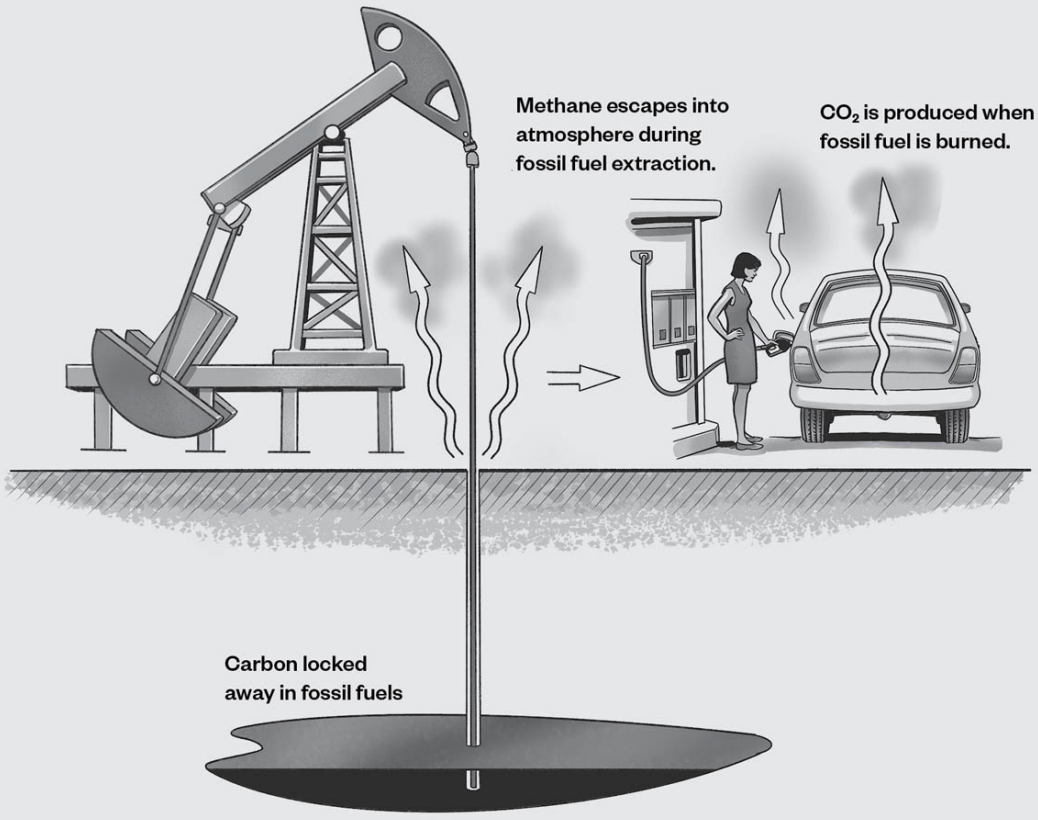


4. Fossil Fuels. Coal, oil, and natural gas are the remains of ancient plants, and when burned for energy the carbon in them is converted into carbon dioxide and water vapor, which enter the atmosphere. In addition, during exploration for oil and natural gas, huge quantities of methane are emitted into the atmosphere.

How we can help. Obviously, the less fossil fuel we burn, the less carbon dioxide must be taken out of the atmosphere. We also need to find ways to capture more of

the methane that escapes during oil and natural gas production and put it to beneficial use. Recent studies have found that almost all of the increase in atmospheric methane levels are coming from oil and gas exploration and refining, not from “farting cows” as is commonly reported.

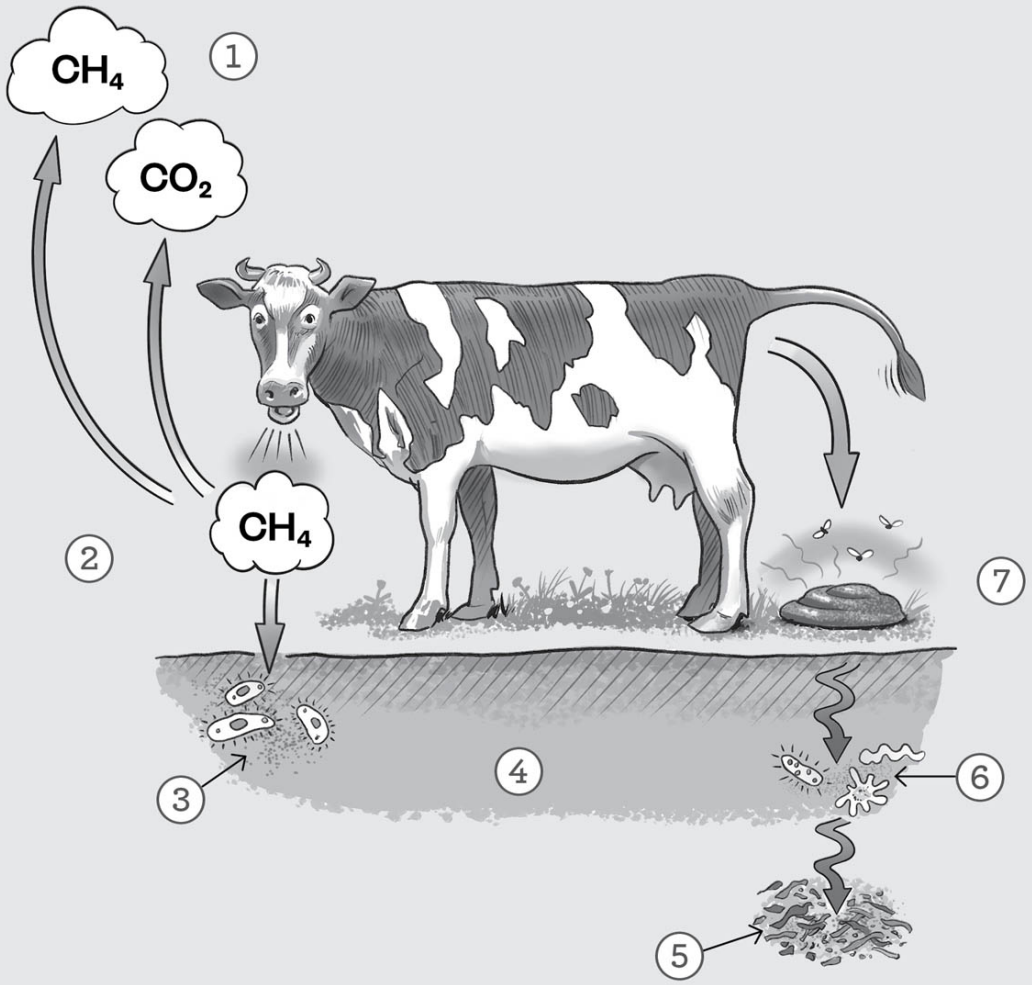
Finding substitutes for the energy we derive from petroleum, natural gas, and coal is critical for reducing our impact on this planet (and also because these sources are finite in nature). All too soon, we will not have a choice in this matter.


Methane escapes into atmosphere during fossil fuel extraction.
CO_2 is produced when fossil fuel is burned.
Carbon locked away in fossil fuels

5. Consumed Carbon. Carbon in plants consumed by herbivores is respirated back into carbon (CO_2), is converted to methane and CO_2 by rumen or cecum bacteria, is excreted in manure, or is absorbed into the bodies of the herbivores or their milk. The animal eventually dies and is consumed by other organisms.

How we can help. The amount of methane emitted by ruminant animals and cecal fermenters has been a matter of concern to many, but this methane emission level is natural and necessary, as herbivorous animals serve vital ecological functions.

To minimize methane emissions from domestic ruminant animals, feed them charcoal, seaweed, and ionophores (feed additives that modify microbial populations in rumens, so they emit less methane) and graze certain plants such as plantain. Keep herbivorous animals on pasture rather than in confinement so they will be in environments where methanotrophic (methane-consuming) bacteria thrive in the soil.



ABOVE:

1. Some methane and CO2 escape into the atmosphere.
2. Methane and CO2 are released by herbivores from digestive fermentation of plant material and animal respiration.
3. Some methane is captured by methanotrophic microbes.
4. Uneaten grass residue and root exudates of pasture plants are decayed by soil microbes.

5. Microbes produce soil humus as long-term carbon storage.
6. Feces are consumed by microbes.
7. Some carbon in ingested material ends up in feces deposited onto the soil.

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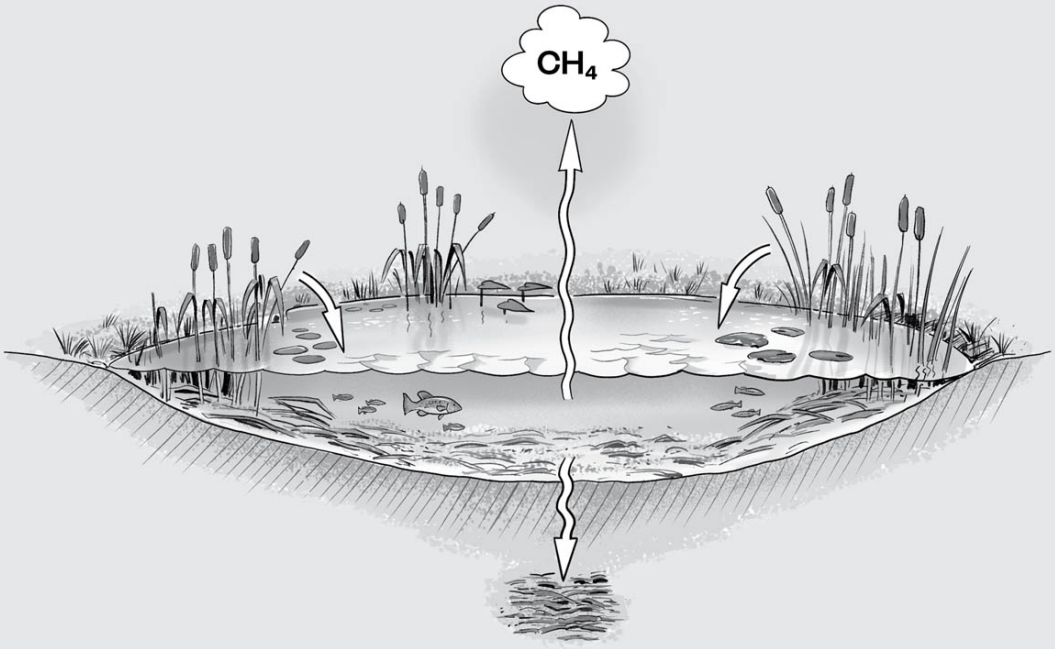
6. Wetlands. Wetlands feature anaerobic fermentation of carbon compounds, which produce methane instead of carbon dioxide. This is important because methane is more potent as a greenhouse gas than carbon dioxide. When methane leaves the animal or wetland, there are certain microbes, called methanotrophs, that consume methane as an energy source. In the atmosphere, methane is slowly converted into carbon dioxide by natural processes, but it resides as methane for an average of 8 to 10 years.

How we can help. Wetlands (including rice paddies) are the biggest emitters of methane on the planet. It would seem logical to simply drain wetlands to stop this methane production. But wetlands are also a highly valuable ecosystem that perform many vital services to the planet. These areas need to be left alone.



ABOVE: *Plant and animal remains settle to the bottom of bodies of water, where oxygen content is often low and anaerobic microbes occur. These microbes emit methane as a product of their respiration during the decay of the organic material.*

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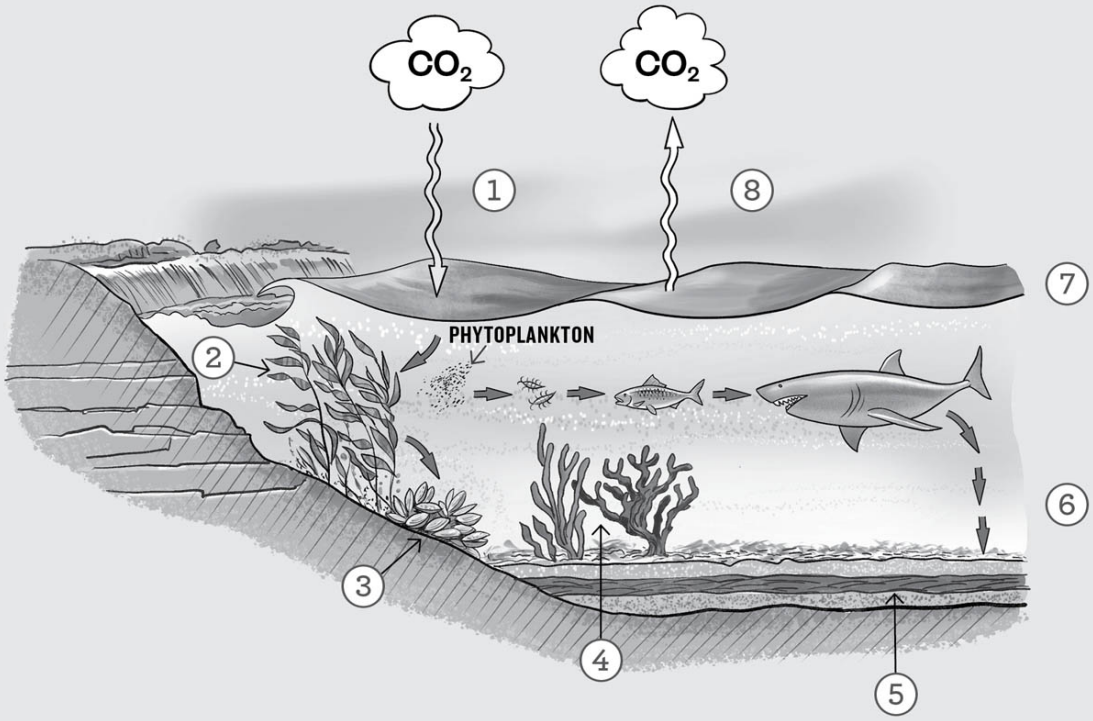
7. Aquatic Organisms. Part of the carbon dioxide in the air, as well as carbon dioxide produced by the respiration of aquatic organisms, becomes dissolved carbon dioxide in water. Part of this CO_2 remains suspended in water, some is used by mollusks to build shells and corals to build reefs, some is used by aquatic plants for photosynthesis, and some combines with dissolved calcium and magnesium in the water to form limestone.

How we can help. Encouraging the growth of hard-shelled mollusks (such as oysters) and coral results in large amounts of carbon being sequestered, since shells and coral reefs are made of calcium carbonate. Unfortunately, we have lost 85 percent of our ocean shellfish population.

Another way to sequester oceanic carbon is from the production of seaweeds such as kelp. Kelp is a very rapidly growing plant and has value as both human food and livestock food, as well as for producing habitat for fish and other aquatic creatures. Feeding kelp and certain other forms of seaweed has also been shown to reduce methane emissions from domestic ruminants and improve their growth rates and feed efficiency.

Since roughly two-thirds of the world's surface is covered by oceans, perhaps ocean farming of seaweeds and shellfish could be a key ingredient in fighting climate change. Ocean farming might also be a means of recovering vital mineral nutrients that have been flushed into the ocean in sewage over the years and returning them to the land. See Ocean Farming: GreenWave.



ABOVE:

1. CO_2 is dissolved into ocean water.
2. CO_2 is used in photosynthesis by seaweed.
3. CO_2 is incorporated into mollusk shells as calcium carbonate.
4. CO_2 is incorporated into coral reefs as calcium carbonate.
5. Carbon is trapped in humic substances from decay of feces and dead animals on the ocean floor.
6. Phytoplankton are eaten by zooplankton, which are eaten by small fish, which are eaten by larger fish, all of which defecate onto the ocean floor.

7. CO_2 is used in photosynthesis by phytoplankton.
8. CO_2 goes back into the atmosphere as needed to maintain equilibrium between ocean and atmosphere.

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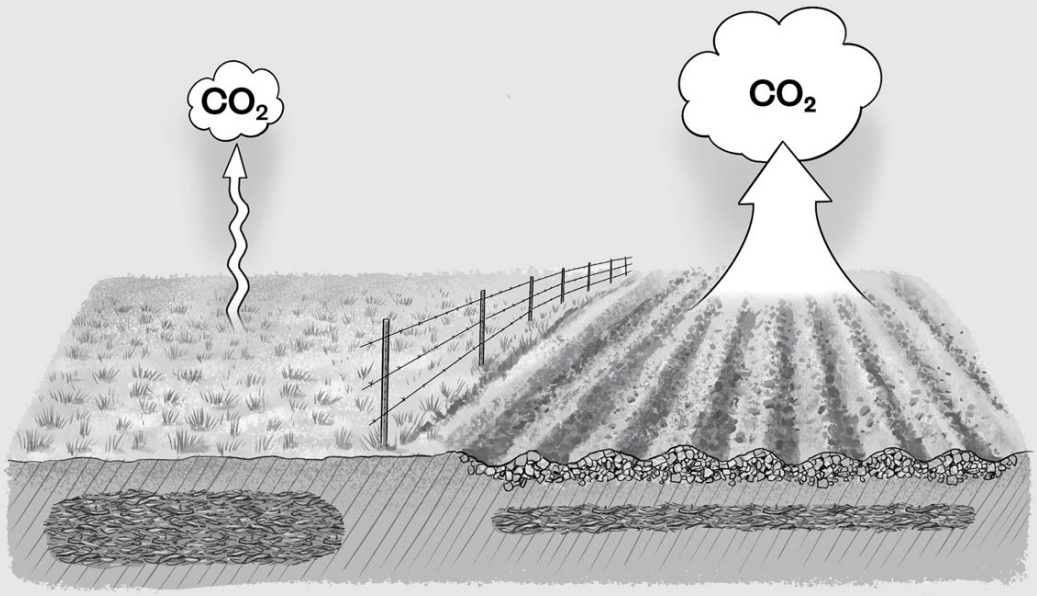
8. Tillage. Some of the long-lived soil carbon compounds (humus) are broken down by soil microbes each year, and the mineral nutrients also contained in them become sources of nutrients for plants. This process is rapidly accelerated by soil tillage. Tillage results in rapid loss of carbon from soil and the release of carbon dioxide into the air, as described in Chapter 1.

How we can help. A major contributor to atmospheric carbon dioxide over the last 7,000 years has been tillage of soil. By most major estimates, roughly a third of the increase in atmospheric CO_2 over the last 300 years has come about because of soil tillage since the settlement of North and South America by Europeans. The other two-thirds has come from the burning of fossil fuels and forests. What we don't know is how much carbon was lost to the atmosphere from tillage in Africa, Europe, and Asia over the 7,000 years prior to our modern era.

The potential of the world's cropland soils to sequester and store more soil carbon is immense. There is tremendous potential to store more carbon in the soils in the world's rangelands and forests as well.



ABOVE: *Tillage of soil in cropland (right) breaks soil aggregates apart, exposing fresh surfaces to microbes. They feed on the soil organic matter and convert it into carbon dioxide that leaves the soil and enters the atmosphere. This emission usually exceeds the level of photosynthesis occurring on the land, so soil carbon levels decrease over time, depending on crop rotation.*

Because cropland that is farmed in a system of no-tillage (left) does not experience this disruption, it emits far less carbon dioxide than the carbon dioxide fixed by photosynthesis on the land. As a result, the level of soil carbon rises on no-till cropland.

Photosynthetic Pathways

Most of the plants common to temperate-area agriculture have a method of photosynthesis referred to as C_3, so named because the first organic acid produced by this process (in the eventual production of glucose) has three carbon atoms. The photosynthesis process has two parts: the light reactions, which require light, and the dark reactions, which do not. The light reactions involve the splitting of water into hydrogen and oxygen. The hydrogen is used in the dark reactions, while the oxygen is a waste product to be disposed of, as we will see later. The dark reactions involve the combining of carbon dioxide and hydrogen (from the light reactions) into glucose.

Photorespiration

In C_3 plants, the light and dark reactions take place in the same cells. This is a convenient arrangement, making it easy to transport the hydrogen back and forth. During sunny and warm days when the light reactions are going very fast, however, there is so much oxygen in the cell from the light reaction that the enzyme responsible for grabbing CO_2 can grab oxygen by mistake. The resulting process ends up *not* producing glucose. This "monkey wrench in the gears" phenomenon is called **photorespiration**.

Photorespiration acts to put a ceiling on plant productivity of C_3 plants during periods of high temperatures and intense sunlight. On hot, sunny days, plants with a C_3 photosynthesis can utilize only about 50 percent of the available sunlight and

may actually lose biomass when leaf temperatures exceed 86°F (30°C). As long as plants have adequate water, evaporative cooling from transpiration can keep leaf temperatures low enough despite high air temperatures. Heat and drought combined, however, can cause C_3 plants to simply stop growing. This is why cool-season grasses such as tall fescue, orchardgrass, and smooth brome grow very little in a typical Midwestern summer. It is also why cereal grains such as wheat and rye do not grow in summer at all in southern locales.

The photosynthesis process has two parts: the light reactions, which require light, and the dark reactions, which do not. The light reactions involve the splitting of water into hydrogen and oxygen . . . The dark reactions involve the combining of carbon dioxide and hydrogen (from the light reactions) into glucose.

THE C_4 STRATEGY

Some plants have evolved a photosynthetic method to circumvent photorespiration, making them productive in hot, sunny weather. This method is referred to as C_4 because the first product has four carbon atoms in its structure. Examples of C_4 plants include warm-season grasses like corn, sorghum, sugarcane, and bermudagrass, as well as pigweeds.

Two mechanisms help these plants avoid photorespiration. The first is the separation of the light reactions and the dark reactions into different cells. The light reactions take place

near the surface of the leaf, closer to the sunlight and where it is easier for the oxygen to escape. The dark reactions take place in a set of cells close to vascular tissue where the glucose can be moved quickly to other parts of the plant. The second mechanism pumps CO_2 from the outer part of the leaf into the inner layer where the dark reactions take place.

Because there is no photorespiration, C_4 plants grow very rapidly in hot, sunny conditions and actually reach peak productivity around 90°F (32°C) with adequate moisture (most C_3 plants are most productive at about 77°F [25°C]). They also can utilize more sunlight than C_3 plants. Due to these advantages, on a hot, sunny day, a C_4 plant can produce three times the daily biomass of a C_3 plant. However, C_4 plants are very unproductive below a temperature of 55°F (13°C), and in temperate regions they have very short growing seasons. C_4 plants are more efficient in the use of water and nitrogen but are lower in protein than C_3 plants and are also less digestible (at similar stages of maturity) by ruminants. Mature residue of C_4 plants tends to be very indigestible and very low in protein.

BOTH APPROACHES WORK

So which plants are better? That is like asking whether linemen or “skill position” players are more important in football. You need both linemen and skill position players for a good team. Likewise, you need both cool-season and warm-season plants in most temperate climates. Cropping systems that utilize both cool-season and warm-season species—either in sequence or in blends—can combine the high summer productivity of C_4 plants with the long growing season of C_3 plants. This makes

soil building more efficient, it makes year-long pasture systems feasible, and it can make cropping systems better.

THE PHOTOSYNTHETIC PATHWAYS OF COMMON PLANTS

C3	C4
Legumes	Corn, sorghum, sugarcane, millets
Wheat, rye, barley, oats	Pigweeds
Fescues, bromes, orchardgrass	Bermudagrass, bahiagrass, dallisgrass
Bluegrass, reed canarygrass	Bluestems, Indiangrass, switchgrass
Ryegrasses	Eastern gamagrass, gramas, buffalograss
Brassicas (turnips, canola, radish)	Chenopods (beets, spinach)
Rice	
Sunflowers	
Nightshades (tomatoes, peppers)	

THE PHOTOSYNTHETIC PATHWAYS OF COMMON PLANTS

Most trees	

Pasture Cropping

COLIN SEIS, NEW SOUTH WALES, AUSTRALIA

One night in 1993, talking in a bar with friend Daryl Cluff over a few beers, Colin Seis of Australia hit on a brilliant idea. Of course, many ideas seem brilliant after a few beers. But when this idea still seemed brilliant the next morning, he knew he was onto something.

You see, in Colin's region of Australia the native grasses are predominately warm season, but the crops the farmers grow are largely cool season. While the native grasses go dormant in their pastures in winter, cool-season weeds thrive in the absence of competition. If weeds could grow in those pastures while the grasses were dormant, Colin wondered, why couldn't cool-season crops, such as wheat and oats? He decided to experiment and, after grazing a pasture down a bit hard in the fall, drilled a cereal grain right into the living sod just prior to dormancy.

Voilà! The crop not only survived, but actually did rather well, yielding no less than crops planted on tilled land with far more expense for inputs. Thus was born the concept of "pasture cropping"—growing a cereal grain in the season opposite that of the predominant pasture grass. Encouraged by this success, Colin has tried all sorts of pasture-cropping nuances, from monocultures of

wheat or oats drilled into dormant warm-season pastures and harvested for grain, to diverse polycultures of cool-season plants that are pastured off just prior to the emergence of the predominant perennial grasses.

While the original appeal of pasture cropping was just to squeeze in an extra cash crop on an extra acre of land, Colin discovered there were many other benefits he did not anticipate. Of course, the financial advantages of adding a cash crop onto the existing pasture are obvious, but that was not the biggest benefit. If you have been following this book and learning that soil organic matter is built largely from microbes that feed on root exudates, it makes complete sense that feeding those microbes root exudates over a longer period during the year would increase soil organic matter.

And that is exactly what Colin has seen—in fact, a 203 percent increase in soil carbon compared to adjacent pastures that are not pasture-cropped. This increase in soil carbon creates more water-holding capacity, an important consideration in drought-prone Australia.

Another advantage of feeding those rhizosphere microbes additional energy over a longer period of the year is an increase in availability of mineral nutrients. In fact, compared to an adjacent pasture that is not pasture-cropped, Colin's soil tests have shown:

- 227% more Ca
- 138% more Mg
- 151% more P
- 122% more Fe

- 146% more K
- 157% more S
- 186% more Zn
- 202% more Cu
- 156% more B
- 179% more cobalt

Apparently, feeding those microbes actually does help aid nutrient availability!

By applying principles discussed in this chapter on improving the capture of solar energy by extending the growing season with a combination of C_3 and C_4 plants, Colin Seis has demonstrated that there is a great deal of potential not only for sequestering far more carbon in the soil than we thought possible, but also for making far more profit than we thought possible!

Capturing Sunlight

JASON MAUCK, GASTON, INDIANA

It was a slide Jason Mauck showed, during his talk at the 2020 No-till on the Plains conference in Wichita, that first showed me how revolutionary this young man's thought processes are. The photo showed a field of ripe golden wheat ready for harvest, an image fit for one of those calendars that depict bucolic farm scenes. He said this was 90 bushel per acre (5940 kg/ha) wheat on June 21.

He then asked the audience, "Is this farmer doing a good job, or what?" The audience all nodded in agreement. Ninety bushel per acre wheat is a yield not many farmers achieve. He then asked why we thought he chose that particular day to take the photo.

"What happens on June 21 in the northern hemisphere?" he asked. "It is the summer solstice, the day with the most available sunlight of the entire year." He went on: "How much photosynthesis is happening on the day of the highest sunlight availability of the year in this field?"

Zero—since the crop was already ripe and finished growing. Despite this field achieving an impressive yield of wheat, if you consider that our purpose in agriculture is to convert sunlight, air, and rainfall into a useful product through photosynthesis, here was evidence that our

current systems are often miserably poor at achieving this goal.

He then showed a photo of his own field on the same day, a green-and-gold-striped combination of two crops: the golden wheat, which was also ready to harvest, but with a green canopy of soybeans just below the ripe grain heads. Like the field in the first photo, this one was ready for harvest—but it was also still photosynthesizing.

How He Did It

To achieve this result, Jason developed the following pattern: fall wheat planted in four drill rows spaced 7.5 inches apart, then a 37.5-inch-wide strip left blank, then another four rows of wheat. In spring he plants the blank strips with two rows of soybeans spaced 20 inches apart. By wheat harvest, the beans are just below the wheat heads.

The planter does some damage to the wheat during planting, there is some competition between the wheat and the soybeans, and the wheat-harvesting process does some damage to the soybeans, so neither the wheat nor the soybeans achieve record-breaking yields. But the sum of the two crops is much better than the two crops grown separately, or in sequence, because the efficiency of sunlight capture is so much better.

Jason is also experimenting with relay cropping in corn and other crops, attempting to make better use of the sunlight that falls on his farm. When you change your

mindset from “How can I raise more corn/soybeans/wheat?” to “How can I capture more sunlight and convert it into something beneficial?” you are suddenly exploring all sorts of possibilities for improved efficiency of sunlight capture. Improved efficiency of sunlight capture creates both economic benefits and an opportunity to create better soil and, in turn, a better planet.

Capturing Even More Sunlight

The productivity of our agroecosystem and the rapidity of our soil-building process are both limited by the amount of photosynthesis performed. There are several ways to increase the amount of photosynthesis on an area. First of all, ensure that all growth factors that can be controlled are optimized so that the most limiting factor to photosynthesis is sunlight capture. In addition, the plant that is exposed to the sunlight is the most appropriate for the conditions and the season, and the duration of photosynthesis is as long as possible during the year. Also, expose the most leaf area possible to sunlight. It is a good rule to never allow sunlight to strike bare soil.

The most efficient plants at converting sunlight into biologically useful energy are the C_4 plants, represented by warm-season grasses and chenopods such as pigweeds. These are also the most water-efficient plants during the heat of summer, when sunlight is most abundant and when (at least in

my area) there is often not much available moisture to work with due to high evapotranspiration rates. Having a warm-season grass occupy the land from late spring through early fall (when air temperatures are above 86°F [30°C] or so) converts sunlight into biomass about three times faster than having that land occupied by a C_3 plant.

Before and after these dates, however, C_4 plants do not photosynthesize much because it is too cold (C_4 plants do not grow below 55°F [13°C], or so). To utilize the "shoulders" of the growing season, when it has either not warmed up enough for warm-season plants or it has cooled down too much in the fall for them, one must utilize cool-season C_3 species.

The Problems with Bare Soil

A bare soil surface is almost always bad. It is vulnerable to the compacting and erosive effects of raindrop splash, running water, and wind. When exposed to sun it rapidly loses moisture. In the summer it often heats up to temperatures high enough to kill soil microbes. It is exposed to ultraviolet radiation, which can kill many soil organisms.

In addition, soil surface not covered by a green and actively photosynthesizing leaf (even when covered by dead plant residue) is an opportunity lost for photosynthesis, whether the products of that photosynthesis are harvested or simply left to feed the soil system. Every day of photosynthesis produces more plant material and more root exudates, and therefore more opportunities for both profit and building soil.

Leaving a soil surface bare at any time is bad, but it is particularly counterproductive when temperatures are conducive to photosynthesis—when the soil could otherwise be covered in a green, photosynthesizing leaf. Each and every day that sunlight hits a surface that is not a green leaf, potential energy for soil building (and economic activity) is lost. This loss of production occurs both when sunlight hits bare soil *and* when sunlight hits a dead leaf.

Land deprived of photosynthesis is not resting, it is starving!

REASONS BEHIND BARE SOIL

So why do we have soil that is not covered in a green, photosynthesizing leaf? It might be because we are in the dead of winter and nothing is growing. It might be because we have just planted a crop and it has not yet emerged or because it has not yet grown enough to form a complete crop canopy to capture all the light. But all too often, the lack of photosynthesizing leaves is due to the land being allowed to remain fallow, with no growing plants.

Sometimes land is fallowed because of a belief that land should occasionally be allowed to "rest." Land deprived of photosynthesis is not resting, it is starving! Other times, land is fallowed to store moisture for the next crop in rotation. It has been found that fallow is a very inefficient way to store moisture (a topic I address at length in my book *The Drought-Resilient Farm*).

Most often, though, fallow occurs because the farmer does not believe the benefits of the cover crop will be enough to cover the cost of planting it, or that a cover crop will actually cost him or her yield. Why else would huge swaths of the Corn Belt be completely brown and dead from September through April every year? It is not due to lack of moisture, since excess moisture is often a problem in spring in the Corn Belt, and it delays planting. There really is no good reason for productive, rich Corn Belt soil to remain idle all winter long and waste all that moisture and sunlight.

If at all possible, every acre should be growing either a crop or a cover crop. Sunlight is too valuable a resource to waste.

RECOMMENDED RESIDUAL LEAF HEIGHT FOR VARIOUS GRASSES AFTER GRAZING

Kentucky bluegrass, perennial ryegrass, buffalograss, blue grama	3 inches (75 mm)
Tall fescue, orchardgrass, bermudagrass	4 inches (100 mm)
Smooth brome, big bluestem, other warm-season native grasses	6 inches (150 mm)
Eastern gamagrass	12 inches (300 mm)

Strategies to Maximize Photosynthesis

Another reason sunlight may strike bare soil lies in pastures in which too much leaf area has been removed by grazing. If you drive through farm country just about anywhere in the US, you will see that the vast majority of pastures are visibly overgrazed. Overgrazed pastures are notorious wasters of sunlight. If you ask pasture operators why they are overgrazing, the answer is almost always that they need to make as much money as they can, so they need to force their livestock to eat every last blade of grass in the pasture.

The idea that overgrazing is more profitable than proper grazing is absolutely incorrect. The most profitable pasture is the one that yields the most livestock product; this results from a combination of pasture yield that allows for a high stocking rate and animals being allowed to select the largest quantity of a diet composed of high-quality forage.

GRAZE MORE BY GRAZING LESS

The highest pasture yield results from pastures managed to maximize photosynthesis, and that results from maintaining a leaf canopy tall enough so that no sunlight is allowed to strike bare soil during the growing season. Eating every last bite will not allow this to happen. In addition, if animals are forced to eat every last bite, they will, out of necessity, consume very indigestible plant parts (such as stems) and have very poor production of meat or milk.

The graph above illustrates how much more productive grasses are when maintained at a 6-inch stubble height after

each grazing episode, as compared to a 3-inch stubble. It seems counterintuitive that you can graze more by grazing less at each grazing pass, but that is exactly how it happens in reality.

This regulation of residual postgrazing stubble height is made possible through well-managed rotational grazing featuring frequent animal moves. It is said that rotational grazing gives you brakes and a steering wheel. The simple act of moving animals to the next paddock before the forage is grazed too low costs virtually nothing other than a few extra minutes a day to open a new paddock. The added productivity of a pasture with improved management can result in more dollars in the rancher's pocket, more meat available for human consumption from the same land area, more root exudates for soil organic matter building, and all the benefits that accrue from higher soil organic matter, such as better infiltration of rainfall and more water-holding capacity.

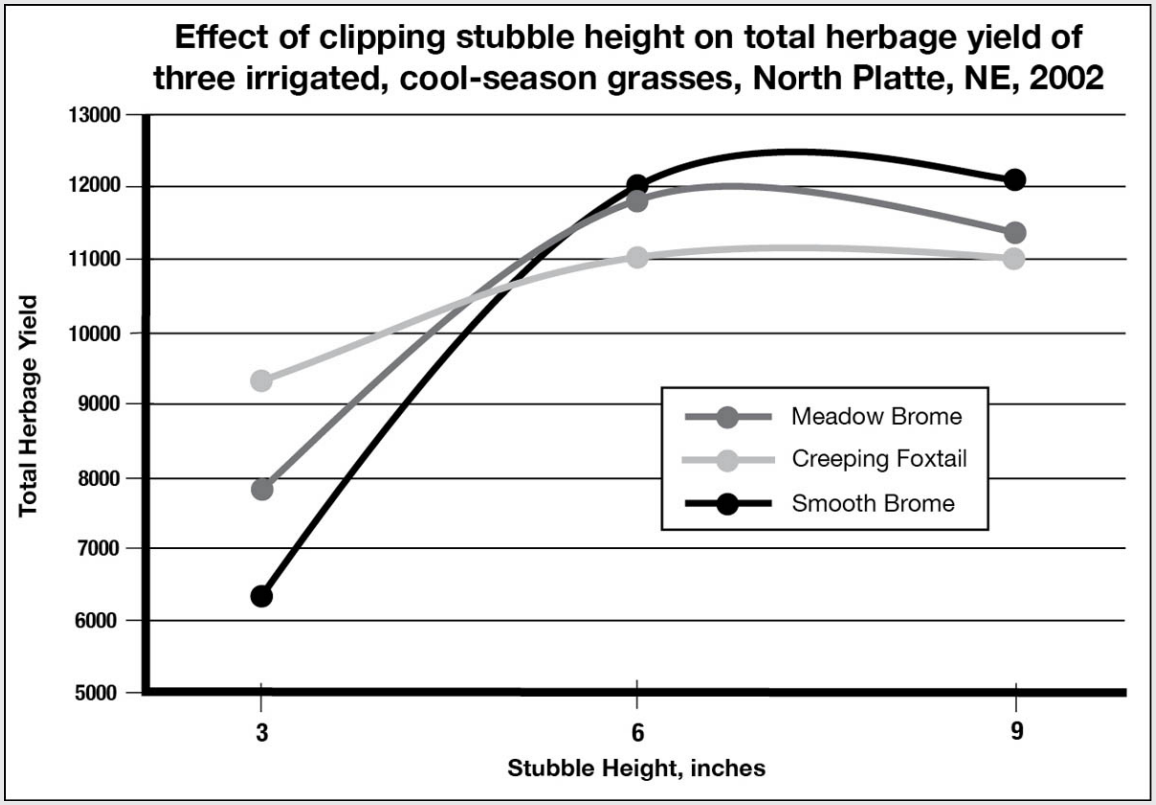
PLANT MORE FORAGE SPECIES

Another way to increase photosynthesis on pastures is to include additional species of forage. One group of species to include is legumes, since most pastures are limited in productivity, and therefore photosynthetic capability, by a lack of nitrogen. Many pastures are lacking legumes because most legumes do not thrive under the heavy continuous grazing so commonly practiced the world over. Yet once rotational grazing is introduced to the system, legumes begin to flourish and nitrogen limitations disappear.

For more on this topic refer back to the profile of Colin Seis.

Grazing Lands and Climate Change

Worldwide, pastures occupy an area that is far, far greater than the area used for crops for direct human consumption. The ability to manage these areas for increased photosynthesis offers more potential to produce more high-protein feedstuffs and simultaneously sequester more carbon out of the atmosphere than any other single practice we have devised for either scheme. So many people blame ruminant livestock, especially cattle, for global warming because ruminants belch methane but fail to realize the incredible capacity of well-managed grazing lands to sequester hundreds of times more carbon in the soil than those bovines will ever belch out.



Source: Jerry Volesky, University of Nebraska-Lincoln

Intercropping Cover Crops

LORAN STEINLAGE, West Union, Iowa

I have often thought that one of the biggest wastes of solar energy on the planet is the sunlight that falls on cornfields between **black layer** *(the date on which corn grain is fully mature) and harvest. This period ordinarily lasts a month or more, since the grain takes considerable time to dry down from the 38 percent moisture at black layer to the 15.5 percent (or below) moisture required for safe storage without molding. That is a month of sunshine falling on millions of acres across the world and producing nothing of value. Then I heard another captivating talk, this one given by Loran Steinlage of West Union, Iowa, on this very topic.*

Loran is experimenting with growing corn not in the traditional 30-inch rows, but in much wider 60-inch rows. This at first seems counterproductive, as a great deal of sunlight hits the soil surface between the rows. Narrow rows capture more of the sunlight than wider row spacing, yet here is Loren going the exact opposite direction, which begs the question: why?

It is what he grows between the corn rows that makes such a difference. Loran uses a system of intercropping full-season cover crops between the corn rows, capturing the light that would otherwise be hitting bare soil. He first

hit upon this system when he was part of a project put on by Bob Recker of Cedar Valley Innovation LLC, studying the use of tramlines, with the rows adjacent to the skipped row in the tramline having their population doubled. They noticed that the cover crop Loran had seeded into the corn grew exceptionally well where the rows were slipped to provide tramlines.

Density and Yield

But how much corn yield is given up with the wider row spacing? Not as much as might be expected; in fact, they saw no yield loss at all. A key is to increase the population within the remaining rows to have the same number of total corn plants per unit of land area. By doing this, most farmers are finding that their yields are only slightly less than that in traditional 30-inch rows.

According to Loran, his yields are almost 100 percent of normal 30-inch rows as long as the population per acre remains the same, noting that not all planters can accurately put out that many kernels per row at normal planting speeds. (Other farmers converting from 30-inch to 60-inch rows have reported anywhere from 85 percent of normal yields to the same yields.) Loran thinks a key to his success in maintaining yields is to apply nitrogen fertilizer to the row, not broadcast. Also, he slows down and plants at 3 MPH rather than the typical 5 MPH to help ensure proper seed spacing and placement to avoid skips and doubles.

Cover Crops Join the Mix

But why make a move to have no more or even slightly less yield? Again, it is what is going on between the rows that is making the difference. The row middles are planted to crops such as forage radish, annual ryegrass, buckwheat, rapeseed, and chickling vetch that remain green long after the corn has hit black layer and is no longer actively photosynthesizing. Not only are these cover crops actively pumping root exudates into the soil and building plant biomass, but they can also provide a substantial amount of grazing after corn harvest, with the high-protein green matter blending well with the high-energy grain left over after harvest.

Loran comments that he did a comparison of companion cover crops seeded at a similar corn stage (around V4 or four-leaf stage) in both 30-inch rows and 60-inch rows for comparison, and the results were dramatic. “I wish we had measured the biomass, but our eyeball estimate was that we had easily five times the biomass in the 60-inch rows. That is a huge gain in grazeable biomass and root exudate production.”

One of the challenges with this approach is weed control, as the traditional long-residual herbicides used in corn production fairly well preclude the use of many cover crops. Loran uses a 10-inch (25 cm) wide band of residual herbicide right over the corn row, leaving the row middles untreated. The row middles are then sprayed using a hooded sprayer to keep spray off the crop (he uses non-GMO corn hybrids, so Roundup is not an option), using a

nonresidual contact herbicide, shortly before the interseeding of the companion crops.

Reaping Sunlight

By harvesting more sunlight, Loran is creating better soil and more harvestable biomass per unit of land area. The openness of the canopy allows more airflow, which reduces humidity on the leaf surfaces and reduces fungal infection, making fungicide applications unnecessary. The diversity of plants attracts a diversity of insects and insect predators, reducing need for any insecticide applications.

All in all, it is a fascinating system that appears to be a much more efficient capture of sunlight and conversion into economic products. If your sole goal is to raise more corn per acre in the upcoming season, then maybe 60-inch row spacing is not for you. But if your goal is to create better soil and more grazeable biomass per unit of land area without sacrificing much (if any) grain yield, then maybe this is a concept you should consider.

PLANT FOR THE RIGHT SEASON

Photosynthesis can also fail to occur when sunlight hits the leaf of a plant that is not photosynthesizing because it is outside of its effective temperature range. This can be an issue in pastures and is a situation that, if solved, can dramatically increase pasture yield. Sunlight striking a warm-season grass

leaf in very early spring is wasted because it is too cold for the grass to photosynthesize. Sunlight striking the leaf of a cool-season grass in midsummer on a day when leaf temperature exceeds 86°F (30°C) is wasted because that leaf will be photorespirating.

MANAGE THE CANOPY

It should be apparent by now that it is not a question of whether a C4 or a C3 species is better; as noted, both groups are necessary. The challenge in a temperate area then becomes how to create a situation in which a blend of C3 plants is allowed to flourish in spring, then give way to a C4-dominated composition, followed by a return to a C3-dominated stand again in fall. This seems simpler than it is in reality. C4 species are very intolerant of shade, and the canopy of C3 species must be removed early in the growth of the C4 species or the C4 species will suffer greatly. In the fall, the dilemma becomes how to remove the canopy of a C4 stand without harming root replenishment (if the C4 species are perennials).

This canopy manipulation can be performed mechanically through mowing or roller-crimping on cropland, or it can be accomplished through canopy removal by grazing animals on pastures. Rotational grazing featuring frequent moves comes to the rescue once again! By confining animals to a small area and forcing them to consume the tops of all plant material before moving, you can remove all the old dead plant material to allow the underlying new green growth to receive sunlight. This also explains why the burning of old dead growth of warm-season grass pastures can actually increase the organic

matter of the soil. The newly exposed growth photosynthesizes at a higher rate and produces more organic matter, building root exudates.

Crop Canopy Architecture

Humans, particularly those of us from Germanic ancestry, seem to like crop canopies that are tabletop flat. Nice, neat, and orderly, but horribly inefficient. Although an oversimplification, one acre of tabletop-flat leaf canopy means only one acre of leaves on an acre of land. If leaves were 100 percent efficient at full sunlight, that would not be a problem; however, leaves of most C3 species reach peak productivity at around 50 percent full sunlight, and C4 species at a bit more than that. In other words, at that point, productivity hits a plateau, and more than 50 percent of sunlight is wasted.

To spread the same amount of sunlight over a larger area of leaf, leaves can be tilted at an angle, which allows more leaves to fit into an area. Tilted leaves tend to produce gaps in the canopy, however, particularly if only one species of plant is present. Multiple layers of leaves are more likely to use all the sunlight, and use it more efficiently, than a single layer. Granted, this can result in a ragged, unkempt appearance that just plain looks ugly to a lot of people. But this “corrugated canopy” creates a far more efficient solar panel.

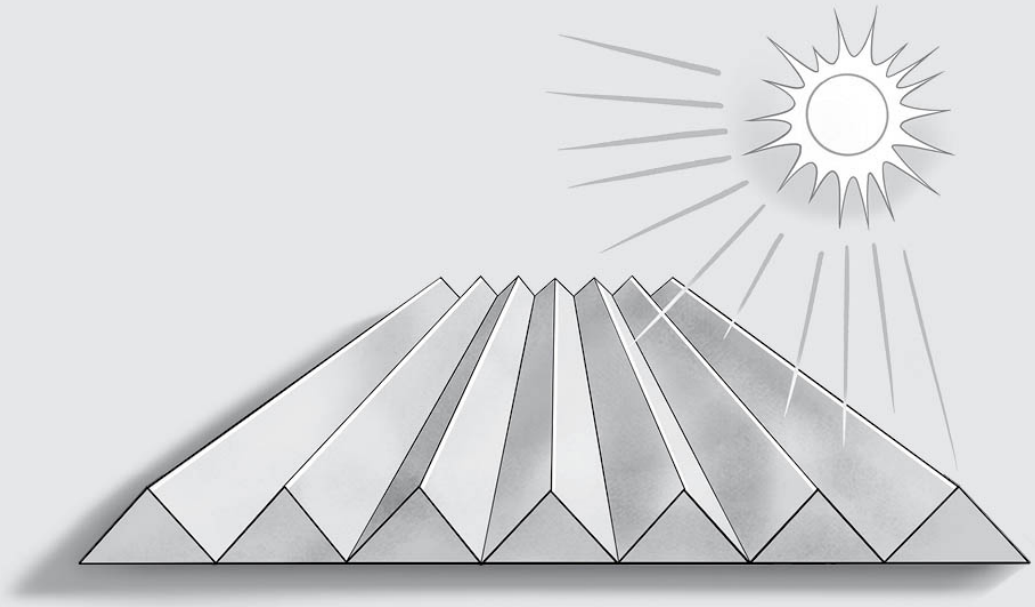
There is more to this than simply producing as much leaf area as possible. When leaves are shaded by other leaves, they use energy but do not produce it. This is why pastures that are completely rested for very long periods of time become

stagnant and lose productivity, particularly those dominated by C4 species in humid environments supporting luxuriant growth.

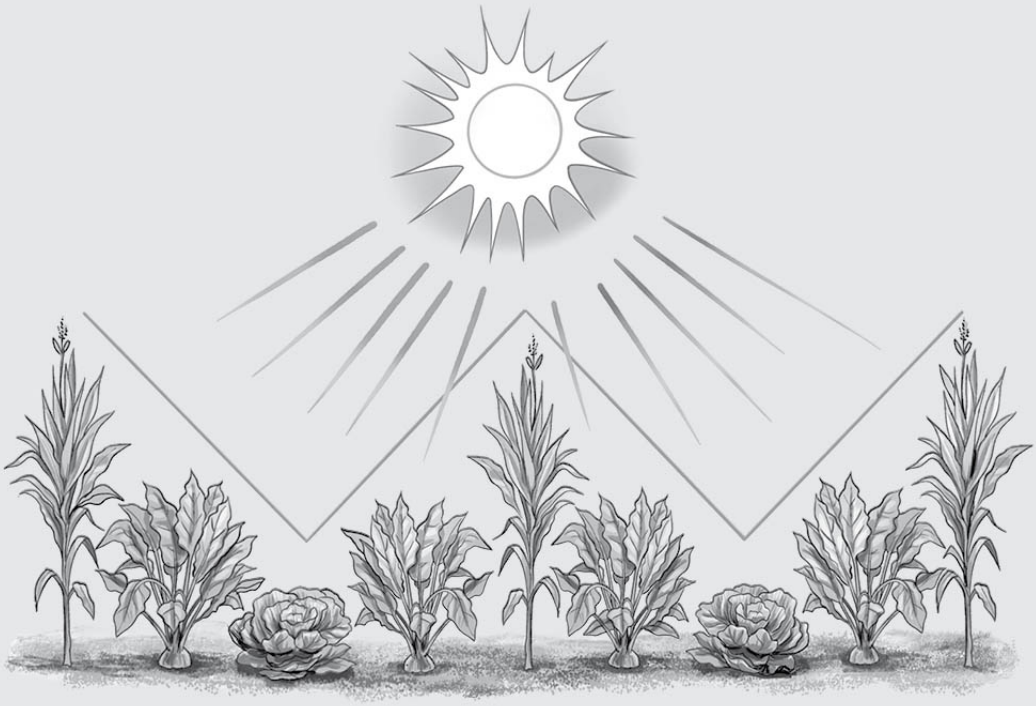
Most grasslands require defoliation to remain productive. There are research plots in some western environments that have had no grazing for decades. One might assume that these areas would be lush in grass. They are not. The old grass residue shades out new shoots, and clumps of grass actually die out.

FLAT VS. CORRUGATED CANOPIES

ABOVE: *An acre of land with a flat canopy of equal-height plants results in one acre of leaves exposed to the sun.*



ABOVE: *With a corrugated canopy, there can be more area of leaf surface than land area.*



ABOVE: *Diversity of plant height and leaf architecture offer more leaf area than a monoculture can.*

Grazing is essential to the grassland; without it, the grassland will not survive.

Grazing and Dormant Forage

Grazing management becomes critical in maximizing photosynthesis. Removal of a percentage of the leaves is not only necessary for a healthy canopy, it is also essential for feeding the livestock that pay for the whole process. Without

grazing, large landscapes have no economic value, and the temptation is far too great to convert it into other uses. Ninety-eight percent of the tallgrass prairie has either been converted into crop production or been covered in concrete. It may be the world's most destroyed ecosystem, and it's largely to due to landowners believing they can increase the value of their property by converting it into cropland or suburban cookie-cutter houses.

Grazing is essential to the grassland; without it, the grassland will not survive, either due to conversion by economic pressures or through self-smothering. On the other hand, if too much leaf area is removed by grazing, then the rate of photosynthesis is dramatically slowed, and root production slows down or even ceases. Since the money is made by leaf removal, however, the almost universal practice is to remove as much leaf area as possible.

This is unfortunate and short-sighted. The excessive removal of leaves at any given point in the growing season will result in less leaf production in the future. Ranchers are understandably reluctant to restrain their grazing pressure, as residual leaf area is seen as "wasted forage" and therefore "wasted money." This is not wasted forage and can be utilized after the onset of dormancy without harm to the plant.

TIMING LACTATION PERIOD TO MATCH GROWING SEASON

While dormant forage lacks the quality of vegetative forage, it is ordinarily adequate for nonlactating animals. Perhaps the most important key to building soil is to make the lactation

period coincide with the growing season. The practice over the past century of birthing domestic livestock in the dead of winter has created the necessity for a higher-quality forage than dormant grasses can provide and has made dormant forage a commodity without an economic value. Without this value, there is no incentive (in the eyes of the landowner) to leave a good residual leaf area going into dormancy. The temptation is to use all the forage during the growing season rather than to leave a healthy leaf area at the end of the growing season.

Weaning at the end of the growing season, and birthing at the beginning of the next one—so that the females are nonlactating during the dormant season—makes the utilization of dormant forage by nonlactating animals a natural process. It also makes complete economic sense to leave a healthy residual at the end of the growing season to last the entire dormant period.

Dormant forage may actually have more economic value than green forage. The alternative to grazing dormant forage is to feed some form of stored forage, such as hay or silage, which is almost always much more expensive than grazing. A key aspect of soil restoration is to make all the steps in the process profitable. Any step that is unprofitable will be sacrificed in a time of financial uncertainty, and in farming or ranching, financial uncertainty is all too often an everyday situation.

Efficient Pasture Design

Designing a pasture for efficient photosynthesis involves some simple principles:

- **Allow C4 plants to have the first shot at sunlight** in the summer, because they will produce the most biomass and root exudates from that sunlight of all the possible plant species, and they are the least shade tolerant.
- **Extend the growing season** with cool-season species that green up earlier and stay green later.
- **Provide for adequate fertility**, particularly nitrogen fertility, either with fertilizer (preferably carbon-based, as described in Chapter 6) or with legumes in the pasture species composition.
- **Create a blend of plants with multiple layers**, with vertical-leaved plants near the top of the canopy and flat-leaved plants close to the soil. Vining plants can exploit gaps in the canopy where other plants are lacking.
- **Ensure that all soil is protected** by a litter layer at all times, and by a green leaf layer for the entire growing season.

Allowing a C4 plant to have first shot at the sunlight in the summer can be accomplished by including either a perennial or annual warm-season grass. In my experience, however, a pasture should have either warm-season perennial grasses or cool-season perennial grasses, but not both. While some very good pasture managers seem to be able to maintain a balance through proper rotational grazing, I have found that aggressive cool-season grasses get a head start on the warm-

season grasses and shade them out, and you end up with all cool-season grasses and no warm-season grasses.

I certainly respect the opinions of those who have been able to maintain a nice balance in their system. Part of the problem with my experiences may be that the predominant cool-season grasses in my area are the highly aggressive smooth brome and endophyte-infected tall fescue; perhaps less aggressive species might change my opinion. In any case, I feel that the optimal time to rest cool-season grass is prime grazing time for warm-season grasses, and vice versa, and a blend does not lend itself to best management of either.

That said, I have found that it is quite effective to have a summer annual grass in a cool-season perennial, and a winter annual grass in a warm-season perennial. Crabgrass is a productive C4 grass that does quite well in cool-season grass sods, as many lawn owners can attest. A canopy of rapidly growing crabgrass above a cool-season grass sod can dramatically improve summer productivity. The crabgrass can be grazed off at the beginning of fall to let sunlight down to the underlying cool-season plants for the fall growth period.

It is a common practice in the southeastern states to interseed annual ryegrass (a winter annual that reseeds well) into stands of bermudagrass, a C4 perennial. Cool-season legumes can also be used. These offer the benefit of adding nitrogen to the system, but they do not typically produce as much biomass as the grasses. Multiple layers of leaves can include a tall, productive grass as the top layer, since grasses have vertical leaves, and plants that have large flat leaves lie prostrate on the ground as the bottom layer, like ladino clover, plantain, or chicory.

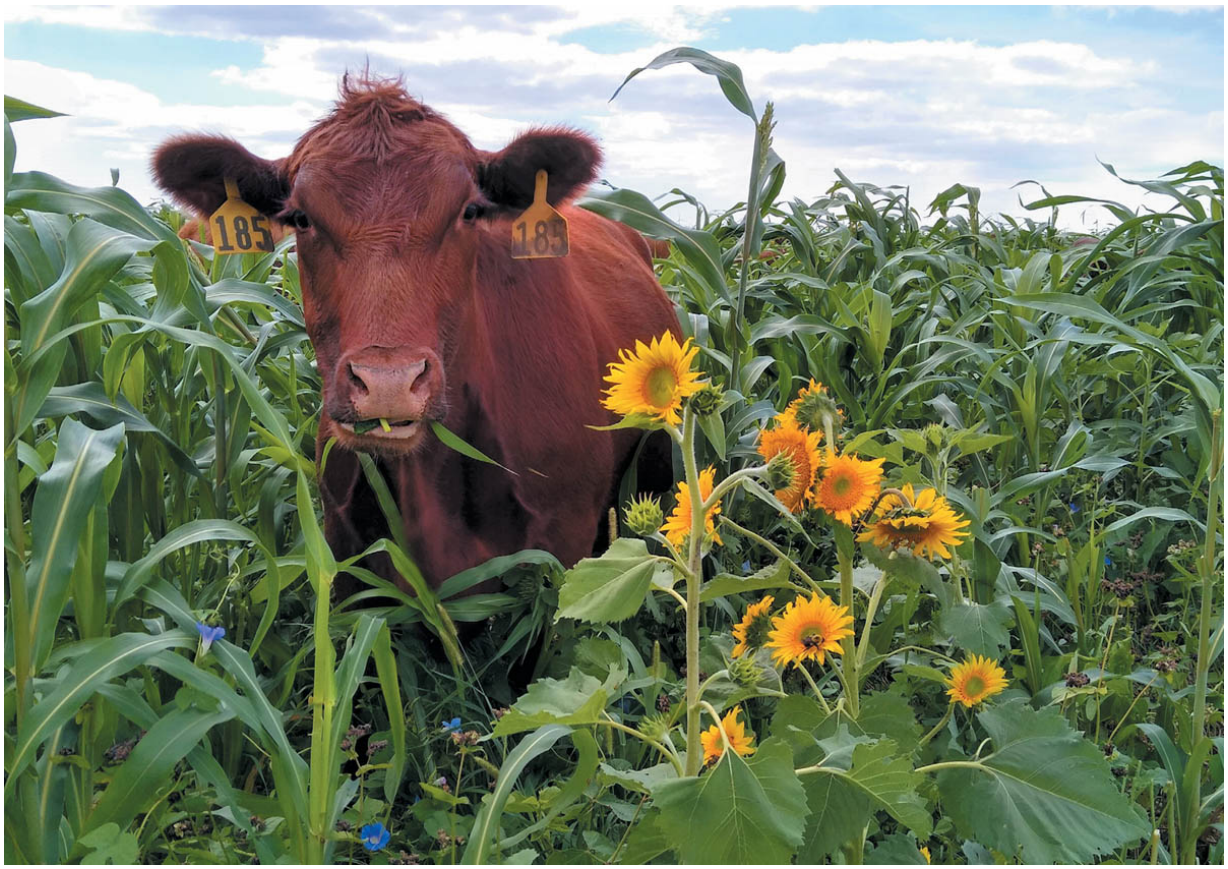
CHAPTER 7 SUMMARY

- Sunlight is the original source of almost all life on Earth; sunlight energy is converted into glucose by photosynthesis, and this glucose is then converted into a myriad of carbon compounds used as biological food or incorporated into the bodies of living organisms.
- The carbon compounds are converted back into carbon dioxide in aerobic respiration or as methane in anaerobic respiration and return to the atmosphere. Carbon compounds can also be converted back into carbon dioxide quickly during oxidation by burning.
- Plants have two primary methods of photosynthesis; one is common to cooler regions and is referred to as C3. The other is more common to hotter regions and is called C4. C4 plants are far more rapid growing and more efficient in use of water and nitrogen but require warm temperatures in order to grow. C4 plants during active growth produce far more root exudates than C3 plants.

Better Practices

Cover Crops

ABOVE: *FIGURE 9.1 Macauley Kincaid in southwestern Missouri holds soil from his no-till cover-cropped field (at left), and compares it to soil from a tilled field with no cover crops. (See* Chapter 10*.)*



ABOVE: **FIGURE 9.2** *A cow contentedly eats a diverse cover crop blend. (See here.)*

ABOVE: **FIGURE 9.3** *Nitrogen-fixing nodules on a cowpea root (See here.)*

ABOVE: **FIGURE 9.4** *A radish hole held open by ryegrass roots allows oxygen and water to penetrate deep into the soil. (See here.)*

ABOVE: **FIGURE 10.1** *Cover crops contribute to beneficial habitats that encourage biodiversity. At right, a pheasant's almost hidden nest in a cover-cropped field. (See here.)*

ABOVE: **FIGURE 10.2** *Cover crops can be managed to produce pollen and nectar. This can feed and build populations of beneficial insects, such as the lady beetles shown here, which can in turn prevent outbreaks of insect pests. (See here.)*

ABOVE: **FIGURE 10.3** *Cover crops can provide nectar and pollen for honeybees as well as for wild pollinators. (See here.)*

Portable Fencing

ABOVE: **FIGUREs 11.1–3** *Portable fencing reels with polywire (plastic twine with interwoven thin metal wires, shown above) and portable step-in fence posts (pictured below) make installation of temporary fencing for rotational grazing fast, easy, and inexpensive. (See* here*.)*

Forest Farming

ABOVE: *GinSeng*

FIGURE 12.1 *A valuable medicinal plant, ginseng thrives in a forest setting. (See* here*.)*

ABOVE: *Shiitake mushrooms*

FIGURE 12.2 *Shiitake mushrooms can convert forest trimmings into a high-value crop. (See* here*.)*

ABOVE: *Goldenseal*

FIGURE 12.3 *Goldenseal is another medicinal herb—one of the best-selling herbal supplements—that grows well in a forest ecosystem. (See* here*.)*

ABOVE: *truffles*

FIGURE 12.4 *Oak trees offer many benefits beyond lumber. Their acorns are nutritious food for livestock and wildlife, and truffles (above), an exceptionally high-value fungus, can be cultivated on the roots of oak trees. (See* here *and* here*.)*

ABOVE: *Maple syrup*

FIGURE 12.5 *Maple syrup has been a highly prized forest product in northern regions of North America for many centuries. (See here.)*

Agroforestry Techniques

ABOVE: **FIGURE 13.1** *Alley cropping is the practice of cultivating herbaceous crops between rows of trees to provide a source of revenue while the trees are becoming established. The crops may offer additional benefits to one another including wind protection, nitrogen fixation, and hosting beneficial insects, such as pollinating bees and predators of insect pests. (See* here*.)*

Savanna Grazing

ABOVE: **FIGURE 14.1** *The fertile soils of grasslands are formed not merely by the grasses themselves, but also by large herds of grazing animals, as shown here on the Serengeti. While excess grazing can cause environmental issues, a lack of grazing can be just as serious. Grasslands that are not grazed soon accumulate excess dead leaf material that prevents sunlight from reaching new growth. Grazing animals are necessary to remove this excess growth, fermenting it in their rumens or cecums into soil-building manure. (See* here*.)*

Indigenous Farming

ABOVE: **FIGURE 15.1** *The landforming practice called the Indigenous American Raised Bed system not only elevates crops but also includes cavities and depressions for capturing and storing excess rainfall for use during later dry periods. This, along with a thick mulch applied to the tops of the beds, provides resilience against periods both of excessive rainfall and of insufficient rainfall. (See* here*.)*

ABOVE: **FIGURE 16.1** *The Indigenous American "Three Sisters" planting method used a combination of corn, climbing beans, and squash in a polyculture that offers synergy both to plants and to human nutrition. The corn provides a trellis for the beans and copious root exudates for the soil, as well as a high yield of calories per unit of land area. The beans provide nitrogen for the other plants and protein for humans, while the squash suppresses weed growth and is a rich source of many vitamins. (See* here*.)*

ABOVE: **FIGURE 16.2** *The Uros tribe, located high in the Andes along Lake Titicaca, builds entire villages on floating islands made from bundles of buoyant reeds. This provides them with lakeside proximity to water and food and with housing and crops that rise with the floods. (See* here*.)*

ABOVE: **FIGURE 16.3** *On the opposite side of the planet from Lake Titicaca in what is currently Iraq, the Marsh Arabs also build villages on islands constructed of buoyant reeds, being harvested here. Two societies, completely independent of each other, developed strikingly similar systems. (See here.)*

PART III

Practices That Build Better Soil

At some point in time, every theory and principle was just an idea, and ideas are of no benefit if never put into action. In the following chapters, the principles we have discussed in previous chapters are boiled down into real-world practices that can build better soil and simultaneously produce abundant food in a profitable manner. While principles are few and universal, practices are many and will vary widely from soil to soil and climate to climate. A practice that works well in a desert may be disastrous in a tropical rainforest, and vice versa.

Therefore, simply learning practices is nearly useless and potentially harmful without an understanding of how a practice affects the availability of growth factors described in previous chapters: soil oxygen, soil water, soil minerals, carbon dioxide, and sunlight. Once those are understood, how to apply or alter these practices to any given particular situation becomes apparent. But it can be immensely valuable to learn about practices that have been successful somewhere, to avoid continually reinventing the wheel.

After all, while the best education is from the University of Hard Knocks and Trial and Error, virtually no one can afford the tuition at that college.

08

Farming without Tillage

We have already explored the soil destruction and degradation associated with tillage, and it should be evident that this practice must be abandoned. But it is not sufficient to say that; we must develop a system of farming without tillage that is just as profitable as or more profitable than farming with tillage.

No-Till Problems and Solutions

With all the very real negatives associated with tillage, you would think that every farmer in the world would be farming no-till by now but, unfortunately, it is practiced on only a distinct minority of cropland. In the US, only about 35 percent of the cropland is farmed no-till at all, and only 10 percent is farmed no-till 100 percent of the time. Worldwide, only 7 percent of cropland is farmed with no-till methods.

Myths and Misconceptions

Why is no-till not more popular? Obviously, there must be either problems with it or misconceptions surrounding it. Following is a discussion of reasons farmers cite for not converting to a no-till system, the drawbacks of no-till—both perceived and real—, and what to do about them.

MYTH #1: "THERE WILL BE MORE WEEDS."

Quite often the biggest fear of farmers considering no-till is a perceived inability to control weeds. Experience has demonstrated, however, that this fear is largely unfounded. If tillage actually controlled weeds over time, we would no longer have weeds after a century or more of the practice. In reality, most of our weeds tend to thrive in tilled conditions and gradually become less problematic without tillage.

For example, many large-seeded weeds, such as common cocklebur, almost disappear when tillage is no longer performed. These large seeds fail to establish without burial by tillage. On the other hand, weeds with very small seeds that can establish well with only slight disturbance will often increase without tillage. Examples of these include dandelion and marestail.

When I still tilled, my major weeds were velvetleaf and cocklebur. When I switched to no-till, my major weed became marestail, while velvetleaf and cocklebur all but disappeared. In no-till, there really aren't more weeds, but there are different weeds.

Small seeds contain very limited energy reserves. They must reach sunlight and begin to photosynthesize very quickly after sprouting; otherwise they simply starve and die. A good thick mulch of crop residue or cover crop residue can greatly reduce problems from small-seeded weeds by denying them access to sunlight, as is discussed in Chapter 10.

Weeds are a sign that we are not utilizing all of the sunlight, moisture, and nutrients we are given, and that to control weeds we should increase our intensity of cropping. In my experience, the most effective tools for weed control do not

involve some new herbicide but rather the use of cover crops and perennial pasture sods in the crop rotation.

MYTH #2: "I WILL BECOME MORE RELIANT ON HERBICIDES FOR CONTROLLING WEEDS."

One of the main reasons farmers use tillage is to kill weeds. Without tillage, much of the heavy lifting for weed control has fallen on herbicides. But does no-till really use more herbicides than tillage farming? Yes, but not much more, and since switching to no-till I have found that I can actually use fewer herbicides. Most acres of cropland in the US receive both tillage and herbicides; if tillage makes herbicides unnecessary, why do tillage farmers still use them?

The primary difference between no-till and tillage farming is that no-till usually substitutes an herbicide "burndown" application for preplant tillage, to eliminate all competing vegetation prior to planting. In other words, there is a total of one more herbicide application per crop with no-till than there is with tillage.

But what about herbicide-resistant weeds? Oh boy, is this currently a hot-button issue as I write this book. Palmer amaranth has recently been discovered in Missouri to be resistant to not only glyphosate but also dicamba, 2,4-D, ALS inhibitor herbicides (such as Imazethapyr), triazines (Atrazine and metribuzin), and PPO inhibitors (lactofen and fomesafen). That does not leave a lot of herbicide options. Many farmers are so scared of herbicide-tolerant weeds that they are abandoning no-till and breaking out tillage tools in droves. Biotech companies are frantically researching how to make crop plants

resistant to different herbicides to expand our arsenal of chemicals that we can throw at weeds. But you cannot solve your problems by using the same methods that created them. New miracle herbicides will only serve to create weeds resistant to those herbicides.

The ultimate solution to herbicide-resistant weeds is to gain an understanding of weed biology, learn the weak points of each problem weed, and exploit those weak points to fight the weed. As noted earlier, I have found that wise use of cover crops can all but eliminate my weed problems because I can select cover crops that capitalize on the weak points of the weeds I am fighting (see Chapter 10 for more information on cover crops).

LEARNING BY DOING

Disarming Your Foes

In 2008 I for the first time faced a soybean field covered in Palmer amaranth that demonstrated complete resistance to glyphosate. The next year, I put that field into a grazing program, and my cows happily ate that amaranth and did well on it. In the severe drought of 2012, that amaranth was the most productive forage in the field, even surpassing sorghum-sudan.

I then planted a perennial pasture mix and inoculated it with mycorrhizal fungi. The Palmer simply disappeared, and I haven't seen it since. Amaranths do not compete in a

mycorrhizal-colonized situation, since they are not mycorrhizal hosts.

A friend who raises seed crops had a very weedy grass-seed production field from which he harvested and cleaned out several thousand pounds of Palmer amaranth seed. He had just bulldozed one of his native grass pastures and wanted to plant a cover crop to prevent the newly bared soil from eroding. He didn't want to spend money on cover-crop seed, so he thought to himself, "Palmer won't cause any problems in a pasture." He spread the Palmer seed as a cover crop. The seed germinated, grew about 2 inches tall, and died.

This is the all-powerful superweed? It simply could not compete in the native-grass soil, which is highly mycorrhizal and has very little nitrogen in the nitrate form. Palmer didn't survive when that soil was purposely seeded at a rate of several hundred pounds per acre.

Thinking about Weeds Differently

You can also expand your thought processes to do battle against weeds. I held a meeting in far western Kansas about a year ago, doing my "cover crops and no-till" talk. Two young men approached me after the talk to say they were giving up on no-till and going back to tillage. I asked why. They said they were unable to control herbicide-resistant Palmer amaranth and kochia. I asked them to describe those two weeds. They said

the plants came up in solid stands, outcompeted everything, and grew whether it rained or not. I asked them if any of their crops could do the same, and they said no.

I suggested that since kochia and Palmer amaranth were so superior to their crops, perhaps they should make kochia and Palmer amaranth their crops. They were stunned and speechless. I continued to explain that besides all the attributes they listed, those weeds were as high in protein as alfalfa and produced the same amount of protein per pound using one-third as much water as alfalfa. If they were to switch from their current cash grain program to a grazing program, they'd stop spending $80 an acre per year trying (unsuccessfully) to kill those two weeds and instead earn money from them. (I am doubtful that they took my advice.)

Developing new crop varieties that are resistant to multiple herbicides is not the answer to herbicide-resistant weeds like Palmer amaranth. We will simply get weeds that are resistant to multiple herbicides. It is already happening. The solution is to create conditions in our field that mimic the conditions found in native grassland, conditions in which Palmer amaranth cannot thrive, or even survive. I am not necessarily anti-herbicide: They can be useful tools that can eliminate the need for tillage, which to me is a greater evil. But doesn't it make much more sense to create conditions in which neither tillage nor herbicides are needed?

Organic No-Till?

One of the justified criticisms of no-till farming as it exists now is that it is highly dependent on herbicides for success. But herbicides are not 100 percent necessary for no-till; they are simply a tool in the box. In Chapter 13, I discuss organic no-till, which uses no herbicides.

MYTH #3: "I WILL NEED TO BUY EXPENSIVE EQUIPMENT."

A no-till planter or drill can be quite expensive, much more expensive than the comparable piece of equipment that works in a tilled system. Planting in a soil that has not been tilled requires a stronger, heavier planter with more attention to the nuances of proper seed placement.

On the other hand, a farmer can get rid of several pieces of equipment: the plow, the disk, the field cultivator, and the huge tractors needed to pull them. Plowing takes an enormous amount of horsepower per unit of plow width. A no-till planter requires much less horsepower per unit width because it is not being asked to disturb much soil, so the tractor can be smaller and cheaper and requires less fuel to operate. Whereas a tillage farmer needs lots of pieces of equipment, a no-till farmer needs only a tractor, a planter or drill, a sprayer, and a combine.

MYTH #4: "THE SOIL WARMS UP TOO SLOWLY IN SPRING."

One perception, especially in the upper midwestern United States where corn is king, is that you must till to warm up the soil in early spring. Tilled soil does in fact warm up faster on a sunny day. But it also cools down more on cold nights, and the concern about cold should be greater. A residue-covered soil has less fluctuation between day and night temperatures, and if temperatures are taken just before sunrise, there is very little difference between the soil temperatures of no-till and tilled soils.

I was speaking at a meeting of US Department of Agriculture Natural Resources Conservation Service (NRCS) employees, when one participant told me that "no-till just doesn't work around here." He said that the soil stayed too cold with no-till, and thus delayed planting, and the late-planted corn would end up pollinating during the hot, dry part of summer and yield less.

I said, "Pretend you are a farmer, and you are trying to decide whether or not you should start planting in the spring of the year. Just then the phone rings, and it is God. Yup, Jehovah himself. And God tells you that if you plant a week later, he will give you an extra 3 inches of rain this summer to use whenever you need it. Would you accept that deal?"

I doubt that any farmers would say no. But that is exactly what no-till can do for you. You can begin planting just as early with no-till as with tillage because there is little difference in soil temperatures; but even if there is a delay, the added moisture-supplying ability of a no-till field can erase much of the yield penalty from later planting.

MYTH #5: "THE SOIL STAYS TOO WET IN THE SPRING, AND YOU CAN'T GET IN THE FIELD AS EARLY."

This goes right along with the "too cold" excuse. When I began no-tilling (along with cover cropping), a friend who had a long history of no-till and cover crops told me that I would eventually develop a soil that will "stay wet longer and dry out quicker."

Read that last statement again. What he told me was physically impossible! A soil cannot stay wet longer and dry out quicker; those situations are mutually exclusive. But after a couple of years I discovered exactly what he meant. The first year or two of no-till, my field was definitely wet longer than the tilled fields were, and I did indeed need to wait a bit longer to plant. As my soil began to change, however, with higher levels of surface organic matter, I discovered that I could plant at much higher moisture levels than my neighbors could because my soil had changed over time.

This same friend posed this idea: "What is the problem with planting in the mud? Mud is a perfect seedbed. The only problem is that our combination of equipment and low-organic-matter soils means planting in the mud will result in soil compaction and sidewall smearing of the seed trench. But what if your soils were not susceptible to those issues, because you now have high-organic-matter soils?"

Sure enough, as my soil changed and began to resemble peat moss—instead of pudding when wet and concrete when dry—I could plant when the soil was quite wet and get perfect stands without yield penalty, because there was no soil

compaction and no sidewall smearing. My soil did indeed stay wet longer, but it didn't actually dry out quicker. What it did do was allow me to plant in high-moisture conditions and get just as good or better results than waiting for the soil to become "dry enough" to plant.

MYTH #6: "THERE WILL BE NUTRIENT STRATIFICATION."

As there is no burial of residue in no-till conditions, the residue (which contains much of the fertility once taken up by the previous crops) remains on the soil surface. Therefore, the surface of the soil tends to become enriched in fertility at the expense of the lower soil layers. It was once thought that this would lead to yield reductions when the surface soil would become dry during drought periods, and there was no water movement into the roots from that layer of soil. These concerns have mostly been found to be a lot of worry over nothing.

In no-till fields, roots tend to proliferate in the top few inches of soil and thoroughly explore that zone for fertility. In dry periods, this layer of soil will retain more moisture than the same layer in a tilled field, and quite often more moisture than the layer below in a tilled field. Nutrient stratification has been proven in research to cause zero yield loss. If nutrient stratification causes you to lose sleep at night, simply use a thin-bladed fertilizer applicator to place nutrients 6 inches deep below the crop row. Alternatively, develop a system in which the soil creates much of its own fertility (see Chapter 6) and the nutrients, instead of being stratified, are everywhere.

See the table on corn root weight.

MYTH #7: "THERE WILL BE MORE DISEASE PROBLEMS."

This perception is based on the belief that diseases are worse in higher-moisture conditions and that any diseases carried on crop residue will persist longer if the residue is not buried. It is very true that disease issues can certainly be worse in no-till, if the crop rotation is too short in duration, especially in the early years after conversion to no-till. In a simple corn–soybean rotation, it is almost a given that gray leaf spot (carried on corn residue) and brown stem rot (carried on soybean residue) will increase in severity because undecayed corn and soybean residue is present on the soil surface, as will many soilborne fungal diseases that proliferate under higher-moisture-presence conditions.

The solution to this one is quite simple: move to a longer, more complex rotation that includes cover crops. This stimulates soil biology that will decay residue and compete with or consume soil pathogens. A good crop rotation should be three or more years in length, with no crop repeated in that period.

MYTH #8: "THERE WILL BE MORE INSECT PROBLEMS."

This concern, like the increased disease pressure, is based on reality. The extra cover provided by surface residue quite often results in more problems from slugs, cutworms, and other pests. But this problem is quite often temporary in nature. Where there is prey, soon there will be predators. I have found that after the first year or so (if you can refrain from

broadcast-spraying insecticides) the population of insect predators (such as wolf spiders, crab spiders, ground beetles, ladybugs, lacewings, meadowlarks, etc.) builds up and provides a mostly complete, but never 100 percent, control of insect pests.

Coupling no-till with cover crops can certainly speed the buildup of predator populations, as can additional crop diversity within the rotation. As described in Chapter 10, adding to the mixture flowering cover crops or companion crops, such as buckwheat or *Phacelia*, can attract many predatory insect species, such as lady beetles and lacewings, that can feed on the pollen and nectar in the absence of prey.

As my soil changed and began to resemble peat moss—instead of pudding when wet and concrete when dry—I could plant when the soil was quite wet and get perfect stands without yield penalty, because there was no soil compaction and no sidewall smearing.

Small-Scale No-Till in West Africa

KOFI BOA, Ashanti region, Ghana

I first met Kofi Boa after he gave a presentation on his work at the Centre for No-Till Agriculture in Ghana. Since 70 percent of the world's farmland is farmed by people who own fewer than 10 acres (4 ha) of land, the potential of making no-till feasible for small landholders is quite literally Earth-changing. In the book Growing a Revolution by David Montgomery, an entire chapter is devoted to Boa's work in promoting no-till among small landholders. I contacted Mr. Boa, and he was kind enough to answer a few questions.

Q: Can you describe the soils and climate of your region, and the farmers?

KB: We are located in the Ashanti region of Ghana. We have an undulating landscape, and soils are mostly silty loam interspersed with patches of stones and gravels. There are some heavy clays in the valley bottoms and sandy loams around river bodies.

The region has a rainfall regimen typical of the moist semideciduous forest zone with an annual average rainfall amount about 120 cm (48 inches). There are two well-

defined rainfall seasons. The major season occurs from late March to the end of July with a peak in May–June. The minor season rains come in September and end in mid-November. August is always cool and dry. There is a long dry spell from mid-November to late March, at which period dry, desiccating harmattan winds blow across the region.

Temperatures tend to be uniformly high throughout the year with mean annual figures around 26°C (79°F).

Food crop farmers in the region are mostly in the smallholder category, and they grow a polyculture of interplanted crops to balance household food security and cash income.

Q: We always hear people say, "I can't afford the equipment for no-till," and yet you are making no-till work without expensive tractors or no-till planters. And people also say, "We can't afford to no-till because we can't afford to buy the herbicides and fertilizers needed for no-till." Yet you are making no-till work with little or no reliance on herbicides or fertilizers. Can you describe how you are planting without preparatory tillage? How are you controlling weeds? How are you providing soil fertility?

KB: As it is the case everywhere, smallholder farmers have limited funds, and so they find it difficult to own equipment. Unlike other places in the world, where no-tillage started on the big farms, we have traditionally been working with smallholders, and we always introduce no-

tillage by showing them how to use their traditional tools to fit the no-tillage system before introducing other appropriate tools.

Farmers use a cutlass to cut down the vegetation, allowing it to dry and burn before digging or planting. We show farmers how to use the same cutlass to clear the vegetation to ensure uniform soil cover and plant through the resultant mulch with the same dibbling stick or cutlass that they use for planting grains in the traditional system. The key is that we first modify the use of their traditional tools to fit the requirements of the no-tillage system before showing other options.

Weed control is still a tricky issue. Industry has become so strong and aggressive that one can easily buy herbicide even in very remote villages. Most of these are generics from China, and most farmers can afford to pay $3.00 or so for a liter.

We have been promoting the use of the traditional hoe, especially for in-crop weeding. Farmers would normally dig the weeds with a lot of soil when weeding with the hoe. Because of that ball of soil attached to the roots, the weeds soon sprout again, especially during the rainy period, which also coincides with the peak of weed growth on the farms.

We teach farmers how to use the same hoe but just cut the weeds at the soil level. This requires less effort and also leaves the cut weeds without soil, so they dry out faster and do not grow back. We also encourage farmers to leave the cut weeds on the soil as cover, instead of their traditional system of cleaning the farm like their bedroom.

We have introduced several cover crops for several purposes, including weed control and fertility maintenance. Crop waste, such as corn husk and cobs, groundnut shells, and other materials that farmers would normally burn or throw away, is recycled. Burning is strongly de-emphasized.

Q: What difficulties have you had agronomically with your system? How have you overcome them?

KB: The major difficulty has been breaking the age-old system of CLEAN SEEDBED preparation resulting from slashing and burning and ploughing with the hoe or tractor. We overcome this problem by showing the evidence of no-tillage on our farms and training plots—for us the trick is, “SHOW IT, DON’T SAY IT.” And of course we build the practical skills of the farmers to be able to plant on the mulch-covered soil.

Q: How have people received no-till? What objections have you had, and how have you overcome those objections?

KB: The no-tillage system has been very well received by farmers in my area, and it keeps spreading, with several NGOs supporting farmers to access training from our Centre.

Q: What results have you seen? What are your successes?

KB: The erratic nature of rainfall these days leads to very poor yields or total crop failure on non-no-till fields, whereas no-till farmers always get some reasonable harvest. Most farmers attribute this to enhanced moisture retention on the no-till plots.

Q: What advice would you give to a small landholder who is considering no-till?

KB: Smallholder farmers are always advised to commit a small part of their fields to no-till and compare that with their normal practice to show the benefits and evidence before committing their entire field to no-till.

Q: What is your future vision for The Centre for No-Till Agriculture?

KB: The Centre for No-Till Agriculture seeks to become the focal point of demonstrating the benefits and evidence of no-till farming so that the technology can sell itself to farmers, whilst at the same time providing farmers with the knowledge and skills to practice no-till farming.

Steps to Making No-Till Work

The most important step in building cropland soil is to stop tillage, but no-till done poorly will result in poor yields and cause many to abandon it and return to tillage. Remember, we have had 7,000 years of practice to learn the farming techniques that work well with tillage. You likely aren't going to become a no-till expert in your first year.

Educate Yourself

That said, ways to self-educate on no-till (or anything else) have never been more available. The internet has made most of the world's information available literally at your fingertips. Search engines, YouTube, and discussion forums all are great helps. There are also countless no-till seminars available, such as the National No-Tillage Conference (put on by the excellent newsletter *No-Till Farmer*) and No-Till on the Plains.

I strongly recommend that you attend these events if you wish to farm, regardless of your experience level, and to connect with other farmers from around the world. The absolute best part of attending these events is not the educational sessions (as good as they are); it is the networking with like-minded people, who can be valuable sources of both technical and emotional support.

Going against tradition can be a very, very lonely journey, and there will be people who honestly want you to fail, because if you succeed, they will appear stupid for not doing it themselves. And chances are, they will not even acknowledge that you succeeded. Do not seek affirmation from your tillage neighbors. You will not receive it. Seek the company of fellow

no-tillers, especially ones who are ahead of you on the learning curve. You will find their company (whether face-to-face or on the phone or by email) much more rewarding than time spent being criticized by neighbors who hope you will fail.

Have the Right No-Till Planting Equipment

Good equipment becomes essential with no-till. A planter must open a furrow, place the seed at the proper depth, firm the seed for good seed-to-soil contact, and then cover the seed. All of these tasks are much easier if the soil is loose, such as with tilled soil. Penetrating soil that has not been tilled is more difficult, and it requires more down pressure on the planting units to press into the soil.

Because of this, a no-till planter is simply a much heavier, sturdier, and better version of a planter. For example, because every force has an equal and opposite reaction, the planter must be heavy to prevent it from being lifted out of the soil.

There are many variations of no-till planting equipment and equipment modifications, but they all boil down to those four main tasks: open, place, firm, cover.

TOOLS TO OPEN THE FURROW

When it comes to opening a furrow, one idea in the early days of no-till was to remove the residue from the immediate area above the row. That led to the invention and manufacture of all sorts of “row cleaners” for sweeping residue to the side. (See Figure 6.1.) Most experienced no-tillers have now removed those devices and have found them to be unnecessary.

But opening a furrow is still necessary, and there are different ways to accomplish this. Some planters use a coulter disk out in front of the furrow openers to create a very narrow strip of loose soil to make everything easier for the equipment to follow. Others use very heavy weights to create strong downward pressure on the planter unit so the disk openers on the furrow opener enter the ground more easily. Others use just a single disk opener operated at a slight angle, with the idea that this takes less downward pressure than a double disk opener does. (See Figures 6.2 and 6.3.)

Another approach uses a "T-boot opener" that acts to create a slot in the shape of an upside-down letter T. The seed is placed on one arm of the T, and starter fertilizer is placed on the other. This seed-placement technique has been highly effective in heavy clay soil.

TOOLS TO PLACE THE SEED AND FIRM THE SOIL

After the furrow is opened, the seeds are placed, and ordinarily there is no difference in the seed-placing mechanisms between planters or drills designed to be operated in no-till versus tilled soils.

When it comes to firming the soil, I have found that a seed-firming device results in far better germination and early-season vigor than otherwise. (See Figures 6.4 and 6.5.) You need to maximize the amount of surface area where seed and soil touch, in order to aid the seed's uptake of moisture. There are several methods to firm soil after the seed is placed.

- Some seed-firming devices (sometimes called lock wheels or press wheels) have little, narrow wheels that push the seed into the trench. (See Figure 7.1.)
- Others attach to the rear of the furrow opener and resemble a thumb that slides along behind it, pressing the seed into the soil.
- Other designs gather loose soil to cover the seed, and then press down on top of the soil above the seed. I find this less desirable than firming prior to covering; I like to have the seed firmed, then covered with loose soil that the seedling will more easily poke through.

TOOLS TO COVER THE SEED

Finally, the seed must be covered to keep the soil around it from drying out. There are many styles of covering devices (also known as furrow-closing devices), ranging from simple drag chains to very elaborate setups. The most successful closing devices are in the form of angled wheels, and some involve spikes. Some work better in clay soils; others, in sandy soils. (See Figure 7.2.)

I have heard several farmers say there is no perfect no-till planter; they all need modification for best function. That may or may not be true, but all of them work best when properly adjusted and maintained for the soil conditions, whether the soil is high in clay or high in sand, and whether it is wet or dry. One of the best educational materials for understanding and fine-tuning no-till seeding is a DVD from Exapta, a manufacturer of attachments that make no-till planters and drills more effective. (see For Further Reference.)

Provide More Nitrogen Fertility during the Initial Years

One of the effects of reduced tillage is that less organic matter breaks down each year. It is important to realize that one of the reasons tillage seemed to stimulate yield was that it oxidized soil organic matter and caused the release of nutrients that were previously stored in that matter. This seemed like "free fertilizer," except that it came at the expense of less organic matter each and every year.

No-till fields will not have this extra shot of nitrogen fertility from organic matter breakdown and will respond to somewhat higher amounts of nitrogen. This also explains why many research trials have shown a yield decrease from using no-till when fertilizer rates were kept the same between tillage and no-till: Often the amount of nitrogen fertility was adequate for the tilled treatment but inadequate for the no-till.

This may seem like a drawback of no-till, but remember that it takes nitrogen to build organic matter, which is 5 percent nitrogen by weight, and this extra nitrogen fertility is being used to build your soil organic matter, which will provide benefits for years to come. It is cheaper to add a little extra nitrogen than it is to import more organic matter.

Including legumes in the crop rotation as either grain crops, forage crops, or cover crops will also aid in supplying extra nitrogen. The table above shows how the yield gap between no-till and plowed soil narrows as more nitrogen is applied.

Additionally, there may be more need with no-till to place fertilizer in the root zone, rather than simply broadcasting

fertilizer materials on the soil surface. The residue on the soil surface often contains urease enzyme, which can cause urea-based fertilizer to volatilize—in other words, nitrogen fertilizers containing the nitrogenous compound urea may break down into ammonia gas and vaporize into the air.

In conventional tillage, this is prevented by using tillage to incorporate fertilizer into the soil. In no-till, there is no such incorporation. Research has indicated that placing the nitrogen fertilizer below the residue and into the soil provides significant yield benefit to crops that require high nitrogen fertility.

HOW NITROGEN AFFECTS YIELD IN TILLED VS. NON-TILLED SOIL

Yield, in bushels per acre. Note that as nitrogen rates increase, the yield difference between plowed and no-till corn decreases. No-till will have less oxidation of organic matter and will respond to extra nitrogen with higher fertility rates.

NITROGEN RATE, LB/ACRE	MOLDBOARD PLOWED	NO-TILL	DIFFERENCE
0	149	123	26

Source: L. G. Bundy, T. W. Andraski, T. C. Daniel, "Placement and Timing of Nitrogen Fertilizers for Conventional and Conservation Tillage Corn Production." *Journal of Production Agriculture*, Vol 5, #2 (1992)

90	160	151	9
180	168	166	2

Source: L. G. Bundy, T. W. Andraski, T. C. Daniel, "Placement and Timing of Nitrogen Fertilizers for Conventional and Conservation Tillage Corn Production." *Journal of Production Agriculture*, Vol 5, #2 (1992)

Spread Crop Residue Uniformly

Without tillage to bury it, piles and clumps of crop residue can lead to difficulties with planting. Residue left in narrow strips behind the combine can cause planting equipment to ride up and over that residue, resulting in uneven planting depth. It is important to adjust the combine chaff spreader to spread residue as widely as possible, preferably to the same width as the combine header. Crop residue can also "hairpin" into the seed furrow, meaning that it is not cut by the opener disks but instead is crimped into a "V" shape in the furrow. It then holds the furrow open and prevents seed-to-soil contact, as well as drying out the furrow.

Practice Agronomically Sound Crop Rotation

Many problems of no-till disappear with a good crop rotation. This is covered in Chapter 9.

Start with a Crop That Is Easy to No-Till

Some crops seem rather indifferent to tillage conditions, while others seem difficult to no-till, at least until the organic surface layer builds up and makes it easier over time. For example:

- Corn is harder to grow no-till than soybeans.
- Large-seeded crops are easier to no-till than small seeds, and legume crops tend to be easier than grass crops.
- Crops that **tiller**, or branch, such as grain sorghum, are more forgiving of an uneven stand than crops that do not tiller, such as corn.
- Crops that are more tolerant of cold and wet conditions are also more tolerant of no-till.
- Sugar beets are difficult to no-till, as beets require very good seed-to-soil contact; they are not a good choice for a beginning no-tiller or as the first crop to be no-tilled in a field.

After the surface layer of soil organic matter builds up, it may be entirely possible to raise these ”difficult to no-till” crops without difficulty.

Start with a Pasture Sod of Killed Legumes and Grasses

One of the easiest no-till experiences I ever had was planting no-till into an alfalfa sod that was killed the previous fall. The legume residue had rotted way, the nitrogen availability was quite high, and the multiple years without tillage while the alfalfa was alive enabled the formation of a nice organic layer that was very forgiving of my poor ability to adjust a planter correctly. Essentially, I was able to fast-forward through those difficult early years of no-till and start at year five of no-till, rather than year one.

Keep the Soil Covered

There is a saying among many experienced no-till farmers: "No-till with no cover is no good." Bare soil left exposed to the sun will often bake as hard as a rock and make it difficult for planting equipment to penetrate. Most of the benefits from no-till are derived from surface cover. Make sure your first no-till experience has sufficient, but not excessive, residue cover.

Address Compaction

Compacted soils can create havoc in no-till fields, especially the first few years. Soil compaction often gets worse before it gets better in no-till. It takes time to build organic matter levels and create macropores. I cringe when people advise others to subsoil before beginning no-till, but I can't deny there are some positive stories about subsoiling during the early years of no-till. However, I strongly prefer to remedy compaction with a

combination of cover crops with deep roots and high amounts of root exudates.

Compaction is alleviated by microbes that create aggregates, changing platy layers into nice crumb structures. These microbes feed on root exudates. If you subsoil, I recommend that you do it *immediately after* planting a compaction-alleviating cover crop or pasture sod. This ensures that there will be no subsequent traffic on the field until the cover crop roots have fully exploited the loose soil created by the subsoiler. As discussed in earlier chapters, any subsequent tillage or traffic after a subsoil trip will eliminate any advantage created by subsoiling.

Remember: "The Best Fertilizer Is the Farmer's Footprint"

Get out and inspect your fields regularly. If no-till results in lower yields, it isn't that "no-till just won't work around here." Less than optimal yields indicate that the plant was unable to obtain needed growth factors or was plagued by a disease, an insect, or weed competition. There is no growth factor supplied by tillage that cannot be supplied by another means.

What are you looking for?

- Examine plants, most importantly the roots. Look for signs of compaction, such as roots that turn sideways or are flattened instead of round. Look for root systems shaped like a tomahawk, which indicate sidewall compaction.

- Test plant tissues for nutrient deficiencies, and diagnose them. Try strips of extra fertilizer to see if plants respond, indicating that they are lacking that nutrient.
- Enlist experienced no-tillers to walk your fields with you.
- Observe, observe, observe.

Small-Scale No-Till

Since most of the world's farmland is farmed by people who own fewer than 10 acres apiece, demonstrating that no-till can work on very small areas of land, with equipment pulled by animals or pushed by humans, is quite literally Earth-changing.

I again recommend that you read David Montgomery's book *Dirt: The Erosion of Civilizations*. The only problem with reading that book is that you will end up quite depressed about what we have done to this planet. Therefore, after finishing *Dirt*, I recommend that you immediately read another of Montgomery's books, *Growing a Revolution*. This book will restore your faith in the future of humanity. My favorite chapter describes the efforts of Kofi Boa in educating about no-till farming in Africa. (See more on Kofi Boa.)

One of the reasons given for the very low adoption rate of no-till in Africa is that most very small farmers believe it requires expensive equipment that cannot be justified for their small acreages. Boa shows how no-till can be accomplished with mere hand tools, requiring no external fertilizers or

petrochemicals and resulting in far greater yields with a fraction of the backbreaking labor that growing crops used to require. Widows who were barely raising enough food to survive with tillage farming are now using Boa's methods to produce salable surpluses with no-till and do so with a fraction of the labor they formerly required. In some cases, yields have increased an astonishing *sixteen-fold*.

The adoption of no-till farming among all the small subsistence farmers of the world would do more for the human race and this planet, in my opinion, than all the charitable projects one could dream up. Remember, if we could increase the organic matter on all the world's cropland by just 1 percentage point, it could return global atmospheric CO_2 levels back to what they were before the industrial revolution.

Small-scale no-till is perhaps the best hope for doing just that.

Organic Weed and Pest Control

One of the best ways to develop a garden that is relatively weed-free and has excellent soil structure is to start with a piece of long-term grass lawn (free of crabgrass, of course) that is killed without tillage. If you are organic, however, killing a perennial grass with neither tillage nor glyphosate seems impossible.

In fact, it can be quite easy to create a vegetation-free environment: Simply place a pen of chickens there for a

month. Boom! No more grass. Even the mighty bermudagrass (almost impossible to keep at bay with tillage and even with glyphosate) will soon succumb to the eager beaks of chickens.

After a month, just move the pen, then plant. Everything you fed the chickens becomes fertilizer for the garden.

If you are in bermudagrass country and fear that bermudagrass will creep back into the garden from the edges, just put a slightly larger pen around the pen that once housed your chickens and now houses your garden. Not only will this keep the grass in check, but it also provides an all-day-long patrol to eat up grasshoppers, slugs, and other pests that try to invade your garden on foot (or whatever it is that slugs use to get around on).

One problem with this method is that the ground is now completely bare, so it might be best to first grow a cover crop and crimp it down, or just import mulch. In any case, even tough perennial weeds and grasses can be subdued without herbicides or tillage and, better yet, get converted into meat and eggs.

Small Scale No-Till Gardening

Many gardeners use tillage as a primary practice, and this is quite unfortunate. The primary reason for tillage is to control weeds, so if a gardener eliminates tillage, an alternative way to

control weeds must replace it. One of the early pioneers of no-till gardening was Ruth Stout, a true visionary. An internet search on Ruth Stout will provide some interesting reading, and she even has videos on YouTube despite passing a generation ago at the age of 96.

Stout authored numerous books, all on gardening using no tillage and remarkably little work. Her key method is to cover the land in a very thick mulch to smother the weeds. To sow seeds and transplant plants, simply pull the mulch aside and open a very small strip through which desired plants can receive sunlight, but weeds between the rows cannot. The mulch not only provides weed control (the single biggest workload of most gardeners), but it also holds in moisture, provides essential mineral nutrients as it decays, and nourishes soil microbes.

FROM COVER CROP TO MULCH

But Stout's methods involve importing mulch in the form of hay or straw. Another approach is to borrow a method from field-scale organic no-till: Grow cover crops and terminate them with a crimper before planting the next crop. Of course a gardener of average scale won't spend the money to buy a large field-scale roller-crimper and a tractor to pull it to use one day a year. (See Figure 7.3.) But innovative gardeners have come up with several creative ideas to terminate a cover crop.

Mini-roller-crimper. One way is to create a small version of a roller-crimper that can be operated by hand or pulled with a regular riding lawn mower. I've seen a design that is simply a

railroad tie with angle irons mounted on each corner to provide an edge sharp enough for a thorough crimp, but not so sharp as to cut the crop. A lag bolt is placed on each end of the tie, with a small pipe and washer over it. A chain is welded to the pipe on each end, and a hitch can be attached to the center of the chain. The device is simply pulled over the cover crop at flowering to crimp it before planting the next crop, and it is surprisingly effective.

Multiple passes are of course an option on a small scale. If the lag bolts and all that seem like too much bother, the railroad tie can simply be rolled by hand back and forth.

Roller-crimper shoes. I have also seen crimper designs that are essentially giant sandals (approximately half the size of a surfboard) with angle irons bolted to the bottom of the sole. You just strap them on and walk the cover crop down. It is not easy work, but it is a good workout that burns calories while accomplishing something useful. Working out while raising incredibly nourishing food is a way to double your impact on your health.

Black plastic. Another way to terminate a cover crop is to lay a sheet of some opaque material over it for a week or two and starve the cover crop for sunlight. I have used black plastic for this purpose and the dark color also causes the plastic to absorb sunlight and heat up, killing the crop by heat. Black plastic can kill a cover crop in just a couple of sunny days. Watering prior to laying the plastic can create steam and make the process more efficient, without making the soil so hot that it

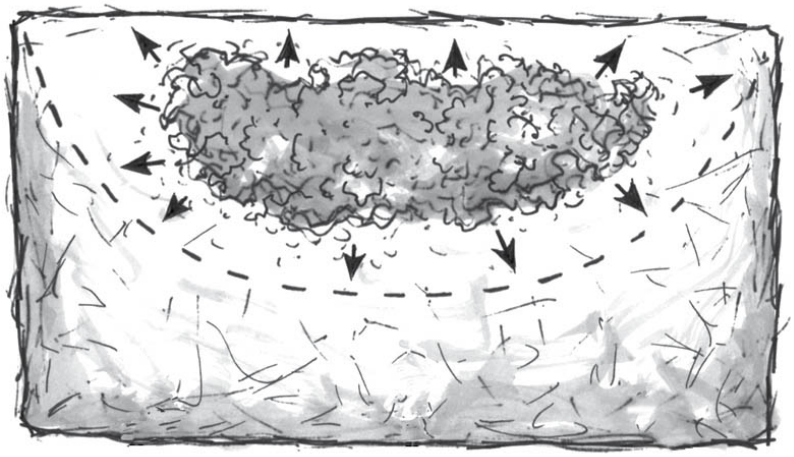
negatively affects soil biology. A soil thermometer can measure soil temperature and make sure the soil does not get too hot.

Of course, you are not limited to one method of weed control. You are certainly free to crimp the cover crop down and lay imported mulch on top for even more weed control and mulch effect. (Using cover crops for weed control is discussed in Chapter 10; using mulches for garden weed control, moisture retention, and mineral fertility in Chapter 6.)

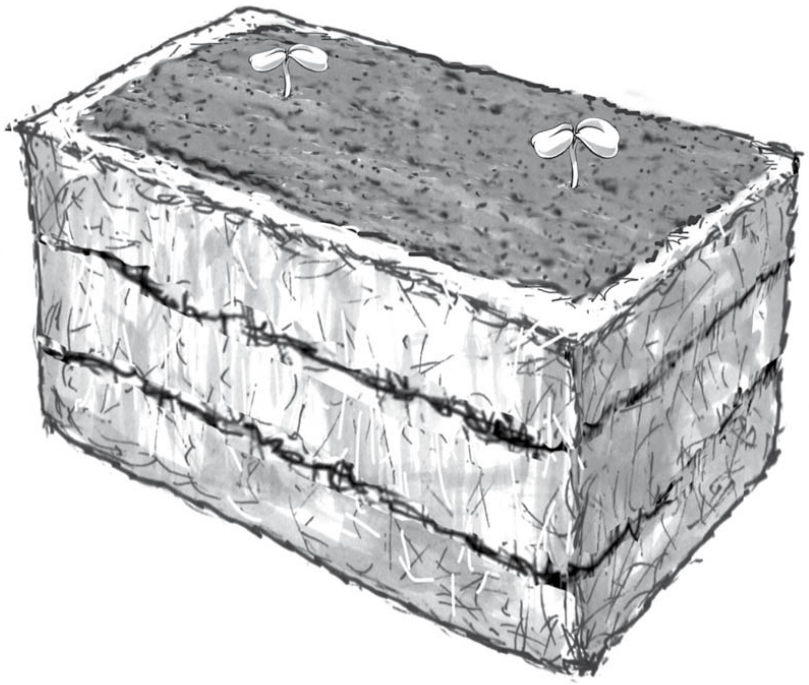
STRAW BALE GARDENING

Straw bale gardening is another way to control weeds and build soil fertility in small-scale gardens (although it does use imported material). The idea is a rather ingenious alternative to planting into soil and covering it with straw mulch.

1. Place a weed-free soil (such as commercial potting soil or soil mixed with vegetative matter and thermal-composted hot enough to kill weed seeds) over unbroken straw bales that have been treated with a nitrogen-rich material (fertilizer or nitrogen-rich organic fertilizer, such as blood meal).
2. Water the layers, and allow them to go through a composting-in-the-bale process (the bale begins to rot, turning from a bale of straw into a bale of compost) until the temperature subsides to normal.
3. Place seed in the thin layer of soil on top of the bales, and water it again.

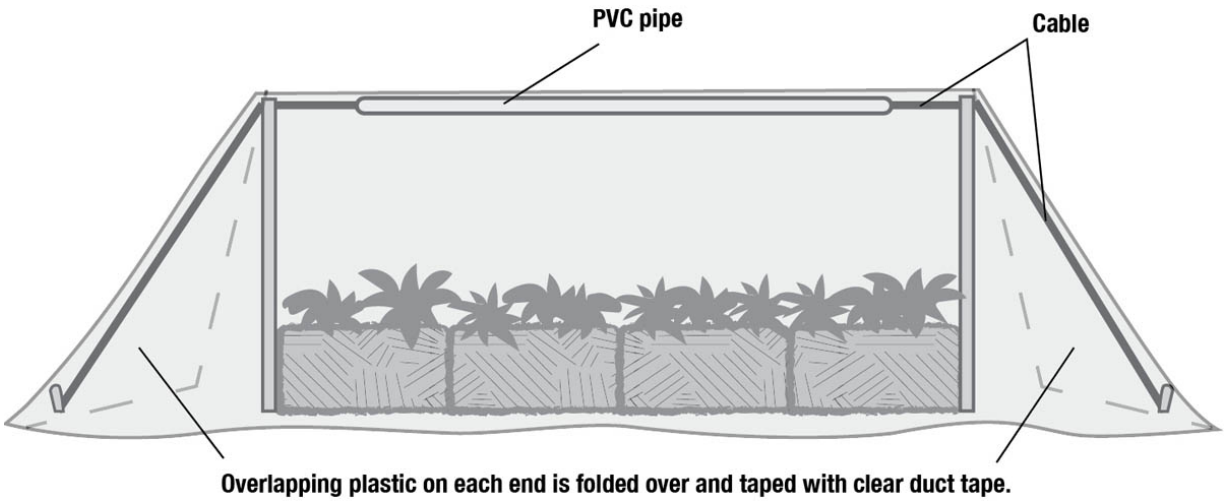


ABOVE: *Weed-free soil and fertilizer atop an intact straw bale compost the straw from the top down.*



ABOVE: *The plants grow in a ready-made, weed-free raised bed: the bale itself.*

An additional spin on this is that a “clothesline” can be placed over a row of straw bales, and a layer of clear plastic can be stretched over the line to form an improvised A-frame greenhouse that is heated by the decay of the bales (see diagram below). There are many books and online resources about this fascinating, low-labor gardening method.


PVC pipe
Cable
Overlapping plastic on each end is folded over and taped with clear duct tape.

CHAPTER 8 SUMMARY

- Farming without tillage has many advantages, not the least of which is better soil in the long term (more soil carbon, better water-holding capacity, less soil erosion, on and on). But farming without tillage requires some adjustments in practices from farming with tillage; it is not as simple as just omitting tillage.
- No-till planting equipment usually needs to be heavier and more sturdily built than planting equipment suited for planting in loose soil. However, though the planting equipment is more expensive, the elimination of tillage equipment and the large tractors required to till soil allows farmers to spend less on machinery.
- There is a perception that no-till soil warms up more slowly in spring than bare, tilled soil. This is true, but not to the degree that many farmers believe. Tilled soils warm more rapidly in the day but will also cool more quickly at night, with predawn temperatures of tilled fields often lower than no-till fields.
- There is a perception that residue-covered soils will dry out more slowly in spring and delay planting. This is true during the early years after transition to no-till, but as a surface

layer of residue and organic matter builds up, the soil becomes more forgiving of planting in wetter conditions.

- There is a belief that disease and insect issues will increase without tillage. Many of these problems can be prevented by an intelligently designed crop rotation, and by the development of a more robust soil biology that occurs after tillage is eliminated.

09

Crop Rotations

Short-term greed has driven a lot of decisions that look rather stupid in hindsight. The corn-soybean rotation, for example, succeeds economically only with high commodity prices that pay for all the expensive inputs necessary to make it work. It is, however, and always has been, agronomically unsound. You are rotating a shallow-rooted summer row crop with another shallow-rooted summer row crop. There is no sod phase, no winter crop, no year-round living roots, seldom any livestock impact, and no close-seeded or deep-rooted planting.

Is There a Better Way to Farm?

Sadly, our entire Corn Belt economy (and, in turn, our national economy) is built on this soil-destroying rotation, so that we can export cheap grain overseas for a few quick dollars. The farmers' fields slowly become impoverished while the agribusiness input manufacturers and grain-marketing channels get wealthy. Our nation's wealth is ultimately built on the very Corn Belt soil productivity we are slowly destroying, and the mineral nutrients (especially P) contained in the grain we ship overseas must be replaced with importation of mined minerals from soon-to-be exhausted sources in faraway lands that are often hostile to our nation.

Overheard on an Ag Talk Internet Forum

This real conversation sums up the dilemma of diminishing choices that often face farmers these days.

Farmer: What can you spray to kill Goss's wilt?

Respondent: Nothing. It is caused by a bacteria. Fungicides aren't effective.

Farmer: How do you control it? My corn is already half dead. Not only is corn half the price it used to be, but I only have half a crop to sell.

Respondent: Resistant varieties and rotation.

Farmer: I planted a resistant variety. I still raised only half a crop, and I can't rotate.

Respondent: What do you mean, you can't rotate?

Farmer: This land I rent was in a corn-bean rotation for years, but sudden death syndrome built up so bad that now soybeans just die off, so I went to continuous corn. Corn makes more money than beans anyway. Well, until you get Goss's wilt.

Respondent: Why not plant wheat?

Farmer: I got this land at a cash-rent auction for $500 an acre. At current prices, I would have to raise 100 bushel per acre wheat to break even. No one in my area has ever raised wheat that yielded that high.

Respondent: True, but with wheat you can double-crop afterwards; that's where you make your money.

Farmer: Double-crop with what? I can't raise beans anymore.

Respondent: How about cover crops?

Farmer: I need a cash crop.

Respondent: Graze them. Beef is high-priced now.

Farmer: I don't have cattle anymore. I sold them all when corn went to $8. I took out all my fences, plowed up my pastures, and bulldozed my ponds in. That cost me a lot of money, but I gained a few more acres.

Respondent: What about custom-grazing your neighbors' cattle?

Farmer: They all got rid of their livestock and plowed their pastures up, too.

Respondent: Do they have Goss's wilt and sudden death, too?

Farmer: Yes. They are all planning on moldboard-plowing their residue this fall. I was hoping there was a better way. Guess I will have to go back to plowing, too.

This is not an evil scheme devised by anyone; it happened because, in America, cleverness is far more common than wisdom. We can change a bushel of grain into an extra dollar by shipping it to a foreign country, which buys it with dollars it received from the United Nations, which received it from the United States in the form of a loan that may or may not be repaid. In the meantime, in the US Corn Belt, two bushels of soil were destroyed in the process of producing that bushel of grain, and we have to import a dollar's worth of fertilizer from that same foreign country to replace the fertility shipped off in the grain.

So is there a better way to farm? Obviously; however, we have a tendency to cling to old methods far longer than we should, when the conditions under which those methods were built change.

Looking Back

In 1973, when many of our nation's current farmers were getting their start, it made complete sense economically (though *never* agronomically) to use machines to put up hay in large bales and haul them to cows standing in a lot, to harvest grain from Corn Belt fields and ship it to western feedlots—and

then to ship the beef back east for consumption. After all, fuel was cheap, machinery was cheap, and the fertilizer (to replace the fertility shipped out in that grain) was cheap.

Conditions have changed, but our farming practices have not. We prefer to sit in the coffee shop and moan about low prices than to change our farming practices and adapt to reality. Does anyone believe that if we complain just a little bit louder the Chicago Board of Trade will give in and raise prices?

Economic Realities and Crop Rotation: Two True Stories

Here are two first-person accounts of crop rotation and its benefits to the bottom line.

ARGENTINA: PIVOTING FOR SURVIVAL

An Argentine farmer told me about economic conditions in his country. When Juan Perón rose to power (for the second time) in 1973 he instituted a socialist government offering many social programs. Argentina has only one major industry, and that is agriculture. When the government changed to socialism, it was a shock to the system. Tax revenue was needed to fund the massive social programs, yet there was only one industry to tax: agriculture. So all imported agriculture inputs were taxed, as were all agricultural exports. Fertilizer, fuel, and machinery became very expensive overnight, and the value of grain and livestock dropped significantly.

Rather than spend their days complaining in the coffee shop, however, or driving tractors to the nation's capital, Argentine farmers adapted. They eventually settled on a crop rotation system quite similar to the one formerly practiced in the Corn Belt: four or five years of an alfalfa grass pasture, followed by a year of corn, a year of soybeans, and a year of wheat, after which the sod was reseeded.

The soil fertility, nitrogen fertility in particular, was built up during the pasture phase and slowly drawn down during the cropping phase. Fertilizer needs in this rotation were minimal, and crop yields were good because of good soil structure and low insect and disease pressure. Even under economic conditions disastrous to most, farmers with this system could thrive.

ARIZONA: LETTUCE TO THE NORTH, WHEAT TO THE SOUTH

The fallacy of short-term profit as a measure of a good crop rotation can be illustrated by a visit I made to an Arizona lettuce grower. The farmer met us as we pulled into the field entrance, with lettuce to the north, and wheat to the south. We asked him if lettuce is a good crop.

"It's an excellent crop," he replied. "We make, in an average year, a $2,000 dollar per-acre profit on lettuce."

My eyeballs must have changed into the shape of dollar signs, as I multiplied $2,000 by the number of acres on my farm—but he quickly deflated my fantasy.

CROP ROTATION IN THE CORN BELT

Going beyond Corn and Beans

DAN DeSUTTER, Attica, Indiana

Dan DeSutter is experimenting with an organic, almost no-till operation, growing corn in a living sod crop of low-growing grasses and white clover. He uses a coulter-type strip-till unit to cut the sod roots in a 10-inch-wide strip in front of the corn planter on 30-inch spacing, leaving a 20-inch-wide strip of clover sod alive in between the corn rows. The sod provides erosion control, nitrogen fixation, and weed suppression, and it regrows back to fill in the corn rows after the corn has had time to grow above the sod.

A machine called a “row mow,” a sort of row-crop cultivator that replaces the cultivator shovels with a mowing unit, controls any escaped weeds that grow above the sod, mowing off weeds right above the clover sod. The residue is blown onto the base of the corn plants to provide a mulch for weed control and moisture conservation, and the clippings of the clover and weeds decay to produce available nitrogen for the corn. Dan is also experimenting with an in-row crimper/roller.

The result is a system that uses almost no tillage (only one-third of the soil surface receives a single shallow tillage pass) and zero herbicides or synthetic fertilizer. In addition, after the corn is harvested in the fall, the sod provides a high-protein supplemental forage for grazing livestock, complementing the abundant but low-protein corn residue.

Dan is also experimenting to see how much, if any, corn yield is sacrificed with wide (60-inch) rows of corn, compared with the benefit of allowing more light to enhance the postharvest grazing. A system like this could make growing corn a quite sustainable form of agriculture.

“It is not a business for the faint of heart,” he added. “We have $4,000 of input per acre, with gross sales of $6,000 to get that profit. Most of that $4,000 is for hand labor.”

Then I asked him who that idiot was, growing wheat next door. “That’s me,” he said. (Open mouth, insert foot.) Wheat is usually considered a low-profit crop, reserved for areas that cannot grow more profitable crops.

So I asked him if he makes money on wheat. “No. We lose about $300 per acre.” I couldn’t understand why he would choose to have half of his acres lose money by growing wheat, when he can make a small fortune from each acre of lettuce. He explained that he once tried to grow lettuce in consecutive years and did not have a single salable head. Total crop failure, with $4,000 per acre invested and then lost.

He explained further: “Bare soil in Arizona can reach temperatures of 140 degrees F. Have you ever put lettuce on a 140-degree surface?” I have indeed, and it wilts and becomes quite unappetizing. He also asked, “Ever bite into a lettuce leaf and get a grain of sand between your teeth?” I’ve done that, too, and it isn’t pleasant.

“That’s what happens,” he said, “when you get soil splashed onto the heads, and that can be prevented by planting lettuce into a wheat straw mulch. Also, lettuce grown too frequently gets diseased. No one will buy diseased lettuce. We grow the wheat so we can have wheat straw mulch on our soil. The straw mulch keeps the soil cool and prevents soil splash, and the year away from lettuce eliminates disease.”

In this scenario, short-term greed would dictate planting lettuce year after year. Yet this would not only court disaster in terms of crop failure but also result in rapid soil degradation, as crops like lettuce—in which all vegetation is removed from the field—lead to rapid loss of soil organic matter.

Rules and Rewards of Good Crop Rotation

Crop rotations are as numerous as there are cropping regions. Obviously, a crop rotation for one of the central valleys in California will be vastly different from a Corn Belt rotation. When designing a crop rotation for your situation, make a checklist of the “rules of rotation” below and see if your plan

meets the criteria. The all too common corn-soybean “rotation” does not.

What Makes a Sound Crop Rotation?

Here are some rules for designing a good crop rotation that I believe will improve crop yields, minimize input costs, and improve soil productivity.

Keep the soil covered at all times, either with a growing crop, a cover crop, or crop residue. Bare soil promotes erosion, invites the sun to kill microbial life and earthworms, reduces infiltration, and loses moisture rapidly from evaporation. Cover is essential to the goals of soil-building.

Replace fallow periods with cover crops. You need root exudates every day possible. Cover crops can also use solar energy to create desirable conditions for the next crop in rotation.

Rotate from one plant family to a dissimilar plant family, such as grass to legume or legume to grass, or grass to forb. There are four main crop groups: warm-season grasses, cool-season grasses, legumes, and forbs. Forbs can also be subdivided into several families as well, such as brassicas (turnips, radishes, canola), chenopods (beets, spinach), composites (sunflowers), solanaceous (tomatoes, potatoes, peppers), lily family (onions, garlic), and so on. The more dissimilar the next crop is from the

previous one, the less likely disease or insect pressure will build. The list below classifies numerous crops by plant family:

- Apiaceae (carrot family): carrot, parsnip, parsley, celery
- Asteraceae (sunflower family): lettuce, endive, radicchio, sunflower, chicory
- Brassicaceae (mustard family): cabbage, broccoli, cauliflower, Brussels sprouts, kohlrabi, turnip, radish, Chinese cabbage, kale, collards, rutabaga
- Chenopodiaceae (goosefoot family): beet, Swiss chard, spinach, sugar beet
- Convolvulaceae (bindweed family): sweet potato
- Cucurbitaceae (gourd family): cucumber, muskmelon, watermelon, squash, pumpkin, gourd
- Fabaceae (pea family): garden pea, snap bean, lima bean, soybean, alfalfa, clovers, cowpeas, other legumes
- Liliaceae (onion family): onion, garlic, leek, shallot, chive
- Malvaceae (mallow family): okra, cotton
- Poaceae (grass family): corn, sorghum, wheat, oats, rye, barley, forage grasses such as fescue, orchardgrass, bluestem, bermudagrass, etc.
- Solanaceae (nightshade family): tomato, pepper, eggplant, potato, husk tomato

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Incorporate legumes in order to build nitrogen fertility on a frequent basis, preferably preceding heavy-nitrogen feeders such as corn in the rotation. Legumes that are grazed will leave

more nitrogen in the ground than ones harvested for seed or for hay, due to return of much of the nitrogen in manure and urine. Nitrogen recycled in manure and urine is usually not well distributed, though daily fence moves can improve spatial distribution of fertility.

Perennial legumes will have more nitrogen in the roots than annual legumes. Incorporating perennial sod on a frequent basis promotes rapid buildup of organic matter and can encourage spore production from mycorrhizal fungi. The data below illustrate how inserting a legume–grass sod can improve corn yield on two different soil types.

HOW SOD-BASED ROTATION AFFECTS CROP YIELDS*

CROPPING HISTORY		CORN YIELD, BUSHELS PER ACRE	
LOAM SOIL	UNFERTILIZED	0-12-12	40-40-40
After corn	62.5	83.7	88.7
After legume–grass sod	69.6	91.7	91.7
CLAY LOAM SOIL	UNFERTILIZED	0-12-12	40-40-40
After corn	45.3	51.4	67.5

*Average yield of grain corn from multiple experiments over a seven-year period (1968–1974) in South Ontario on two different soil textures

HOW SOD-BASED ROTATION AFFECTS CROP YIELDS*

After legume–grass sod	72.6	94.8	99.8

*Average yield of grain corn from multiple experiments over a seven-year period (1968–1974) in South Ontario on two different soil textures

Rotate crops that have different life cycles, such as winter annual to summer annual to perennial. This facilitates weed control and keeps living roots in the ground at all times.

Rotate crops typically grown with wide row spacing (corn, cotton) with narrow-row crops such as wheat or oats.

Maintain rotation for at least three years (four years is better), with no single crop represented more than once every three years. The longer the crop rotation, the less likely disease or insect issues will arise. Few disease organisms can survive more than two years without a suitable host.

Incorporate grazing into the rotation whenever an opportunity arises. This can be grazing of perennial sods, cover crops, or crop residue. The soil-building value of manure exceeds the soil-building value of the plant material from which it came. However, grazing should not continue to the point of exposing bare soil.

Rewards of Rotation

The benefits of following the rules of rotation are demonstrated by the increasing corn yield in the study shown on the previous page. Note that the longer and more complex the rotation, the more corn yields improve. These results have been duplicated over and over again in rotation studies around the world.

Additionally, crop rotation results improve when grazing is integrated into the rotation. Few research studies incorporate grazing because this requires plot sizes that are large enough to carry animals, vastly increasing the size and expense of the trials. Actual farmer experience bears out the benefit of incorporating grazing into the rotation.

As evidenced by study trials, the less frequently corn appears in the rotation, the better the corn generally yields. The fine, fibrous roots of wheat were more beneficial on the heavy clay soil than on the loam soil, while yields were slightly reduced by corn after wheat—likely due to the high carbon-nitrogen ratio of the wheat residue. This is overcome by the high-nitrogen residue in the red clover year.

Improving on a Familiar Rotation

All too often, crop rotations are built around short-term economic return rather than long-term agronomic effect. While it is obviously essential that land produce a profit, simple rotations of the two most profitable crops of the area often require expensive inputs to maintain yields.

Incorporating crops into the rotation that are initially less profitable but agronomically sound will improve future crop yields and reduce the need for expensive crop inputs by improving soil fertility status and reducing pressure from weeds, diseases, and insects.

The less frequently corn appears in the rotation, the better the corn generally yields.

Crop Rotation with Potatoes

BRENDON ROCKEY, Center, Colorado

Potatoes have a reputation for being hard on soil. Since their edible part is underground, harvesting involves digging, and that disturbance is destructive to soil. Most potato growers just accept the fact that their soil will never be any good. They grow potatoes on irrigated land to compensate for the lack of soil water-holding capacity and apply massive amounts of synthetic fertilizer to compensate for the lack of soil fertility and biology.

In addition, since appearance is so important with this product, there is a lot of pressure to produce large, cosmetically perfect potatoes without blemishes. Nematodes are especially destructive to potatoes and can cause enough yield loss and cosmetic damage that the tubers risk being rejected for sale. The fear of putting hundreds of thousands of dollars into a crop that might be rejected makes many potato growers resort to fumigants and nematicides to combat nematodes. I don't blame them. If I risked those kind of input costs I might likely do the same thing.

But Rockey Farms raises potatoes quite differently. They used to do it the way almost everyone else does, in a

rotation with malting barley. Water shortages in 2001 forced them to abandon barley for less water-intensive sorghum-sudan, a nonhost for the nematodes that plague potatoes and a great builder of soil health. After a few years of using monoculture sorghum-sudan in the rotation, Brendon Rockey met Jay Fuhrer of the North Dakota Natural Resources Conservation Service, who convinced him to plant a diverse multispecies blend of cover crops instead.

Turning Point

At this point their soil health took a big leap forward. Potato yields increased, input costs decreased, and the number of low-quality potatoes plummeted. This convinced Brendon that working with nature was the key to success and led him to further trials.

He introduced companion crops among his potatoes, and that roster now includes spring peas, chickling vetch, buckwheat, chickpeas, and fava beans, which attract beneficial insects and add nitrogen to the system. Cattle and sheep now graze a sorghum-sudan–based summer cover-crop blend providing a cash return on the cover and converting aboveground biomass into soil-nourishing manure. Strips of flowering plants throughout the field attract lady beetles, lacewings, and other insect predators to aphids, which transmit some severe potato diseases. Meanwhile, Brendon keeps tillage trips to the bare minimum.

Altogether, the system has eliminated the need for many inputs, greatly reducing his input costs: Brendon estimates he spends $300–$500 per acre less than most potato growers. He is not certified organic, since he occasionally uses some urea, and a desiccant to preserve harvest quality. He uses no fungicides, insecticides, herbicides, and nematicides, not even the ones approved for organic use, allowing him to raise potatoes without toxic inputs. He also uses very little synthetic fertilizer.

Brendon stresses that it is not possible to simply eliminate these synthetic inputs, as many organic farmers attempt to do, without the quality of the crop suffering. It takes a simultaneous commitment to an entire biological system to make it work.

Higher yields with lower costs is obviously a good thing for Rockey Farms, but his system also works for his consumers. Not only are the potatoes raised free of the "-cides," but the high biological activity in the soil also gives them a really wonderful flavor. As a consumer of Rockey potatoes myself, I can testify that they are without question the best potatoes I have ever tasted!

Sample Rotations

Higher yields and lower input costs are a great recipe for increased profit; low yields and high input costs are not. Below is an analysis of some common Corn Belt rotations, followed by

suggestions to improve their agronomic impact. I'll give an example of a very poor crop rotation—possibly the most common one in the US—and my critique of it.

A POOR ROTATION

SUMMER 1: Corn

WINTER 1: Fallow

SUMMER 2: Soybeans

WINTER 2: Fallow

Pros: Rotates grass with legume

Cons: Both crops have summer life cycle; both crops have typical wide row spacing; no sod phase; only two years in length; no cover crops used; no animal impact (unless stalks are grazed)

A BETTER ONE

SUMMER 1: Corn

WINTER 1: Fallow

SUMMER 2: Soybeans

WINTER 2: Winter wheat

SUMMER 3: Fallow

WINTER 3: Fallow

Pros: Has two summer crops and a winter crop; rotates warm-season grass to legume to cool-season grass; is three years in length

Cons: Still has long fallow periods; no sod phase; no animal impact

A LARGER UPGRADE YET

SUMMER 1: Corn

WINTER 1: Winter rye-based cover crop blend (grazed)

SUMMER 2: Soybeans

WINTER 2: Winter wheat

SUMMER 3: Cover crop blend following wheat harvest, with both summer annual and cool-season annual crops (grazed)

WINTER 3: Cover crop blend persists

Pros: Takes three years; no fallow; cover crops eliminate long fallow; rotation of both life cycles and plant families; diversity of plant families; animal impact is included

Cons: No sod phase

EVEN BETTER

Four years of alfalfa-grass pasture, followed by the three-year crop rotation above.

Pros: If the grains are fed to livestock in order to generate manure on-site to conserve organic matter and fertility, so much the better. No crop appears any more often than once in seven years (except the perennial sod). This rotation can be used to include pasture for ruminants, but can also feed poultry or swine with the grain produced.

This final rotation is very similar to the classic Argentina crop rotation (see here) and would be an ideal model for the US Corn Belt to follow. Rather than complain about Goss's wilt, sudden death syndrome, high prices for inputs, and low prices for corn and soybeans, American farmers could follow the lead of the farmers and ranchers of Argentina who have had to deal with artificially low commodity prices and artificially high-priced inputs for decades.

Can You Afford to Put Good Cropland to Pasture?

Most farmers who have seen the evidence agree, I believe, that putting cropland to a grazed pasture sod, or even a perennial hay crop such as monoculture alfalfa, will increase soil productivity over time and pay long-term dividends. But when I approach them with the idea, they tell me they would love to, but they just can't afford to "sacrifice" high-priced cropland by putting it into pasture.

Why is pasture considered a low-value use of land? Let's make a comparison. In my region of mostly corn and soybeans, the highest-revenue-per-acre crop is usually considered to be alfalfa for hay. The acreage is limited because this is a time-demanding crop, due to multiple harvests per year. Harvest is also labor-intensive: The crop must be swathed four times a year, raked four or more times per year to hasten drying, baled four times; and all the bales need to be moved and stacked at least once, often multiple times.

If you add all this together, I figure it costs over $200 per acre just for harvest costs. That is the equivalent of the entire revenue of a 50-bushel-per-acre (3,300 kg/ha) wheat crop sold at $4 a bushel, so it isn't just chump change.

The typical path for this alfalfa hay is to sell it through a broker (who takes a cut), who hires a trucker (who gets a cut) to move it to someone who feeds it to steers standing in a pen (with the hope of making a profit), and who will at the end of the feeding period scrape up all the manure produced and haul it out to one of his fields. Meanwhile, the hay producer will take a generous chunk of the money from the hay proceeds and buy fertilizer to replace all the nutrients that left on the hay truck.

If, however, you take this same alfalfa plant, fence it off and rotationally graze it, you: eliminate that $200-per-acre harvest cost; add that $200 per acre to the bottom line for

the crop; eliminate the money paid to the hay broker and add it to the bottom line; eliminate the money paid to the trucker and add it to the bottom line; transfer the profit made by the livestock feeder to your bottom line; avoid the cost of manure hauling; and by keeping the manure in the field where the hay is being produced make commercial fertilizer unnecessary.

If growing alfalfa for hay is profitable, then how in the heck is pasturing the same crop and eliminating all those expenses not *more* profitable?

The problem is not that pasturing is inherently unprofitable. The problem is that the status quo grazing management is so miserably poor. If pastures are managed properly, they are more profitable than grain crops. But proper pasture management requires a great deal of thought, and thinking is an all too infrequently practiced endeavor. To learn more about proper pasture management, read Chapter 11 on grazing, and if you want to learn yet more, please check out my book *Managing Pasture*.

The Corn–Soybean Rotation: Shaking It Up

Convincing farmers to break out of the familiar and comfortable corn–soybean rotation may require out-of-the-box thinking. (See Figure 8.1.) Here are some innovative crop rotation ideas pioneered by creative farmers with whom I have been privileged to associate.

I admit, my favorite pasture species is eastern gamagrass. Compared to other temperate warm-season grasses, it is much more productive and also highly palatable and nutritious. It is very deep-rooted and tolerates flooding. With all these attributes, one would think it would be planted over millions of acres; yet it lies in obscurity, with very few people knowing even what this most valuable of North American native grasses looks like.

One reason this grass is so seldom used is that it is a poor seed producer, and seed is usually quite high in price. In addition, the seed is highly dormant and needs special treatment to make it germinate. But probably the main reason for its limited use is that, in most cases, it takes at least one full season, and often as many as three years, to establish a good stand.

However, as with many other agronomic challenges, farmers have found ways to overcome these drawbacks (with the exception of the high seed price, which isn't likely to go down unless we find a way to dramatically increase seed production per acre):

- **Plant in late fall rather than spring.** That way, seed dormancy can be overcome the way it is in nature, where the seed drops in the soil in fall and is exposed to freeze and

thaw cycles over winter, which naturally break the dormancy.

- **Inoculate with mycorrhizal fungi.** Eastern gamagrass is extremely mycorrhizal dependent and will have several times the first-year biomass if colonized.
- **Plant gamagrass and corn together.** This allows a cash crop to be produced during the year gamagrass is establishing, when it should not be cut or grazed. Eastern gamagrass is shade tolerant enough to grow under a corn canopy and seems to develop just as well as in full sun. It is tolerant of most herbicides labeled for corn (but not the glyphosate used on Roundup Ready corn!).

My Recipe

In my own experience with gamagrass, I have taken advantage of these traits to come up with the following recipe for success establishing gamagrass:

1. **Plant gamagrass in late fall**, along with a winter cereal grain such as triticale intended for forage. Inoculate with mycorrhizal fungi. The cereal will emerge shortly after planting, but the gamagrass will wait until the following summer. The cereal provides erosion control and weed control—and revenue in the following spring.
2. **Harvest the cereal grain for forage** when the gamagrass is ready to emerge (usually when the soil temperature

hits 60°F (16°C). This lets the gamagrass seedlings have full sunlight.

3. **If herbicides are an option** in your operation (if you are not certified organic), apply a small amount (less than 1 pound per acre) of atrazine for weed control right after the forage is removed. If things work out, this should be the last herbicide application needed for decades.

4. **Plant corn no-till** over the top of the gamagrass. If feasible, it works best if the corn is planted midway between the gamagrass rows, each on 30-inch centers, to provide the gamagrass the most possible sunlight.

5. **Harvest the corn early,** if possible. This will open up the canopy and allow the gamagrass to receive more sunlight. Options include silage, earlage, high-moisture corn grain, or simply choosing short-season varieties.

6. **Determine whether the gamagrass stand is sufficient.** It takes only one plant every 3 feet to provide an eventual satisfactory stand. If the stand is not satisfactory, you can plant to another winter annual crop of cereal, and the following spring go to corn again, to see if any more seedlings emerge while the corn is growing; it may not be necessary to add more seed, as more seedlings may come up. Gamagrass does reseed well, so if the existing plants are allowed to reseed the stand will thicken. The seedlings will need to go through winter and another full growing season before grazing, but corn can be planted each of those years.

7. **If the stand is satisfactory, you can either interseed** perennial companion legumes, grasses, and forbs (I like alfalfa, white clover, Korean lespedeza, bird's-foot trefoil, chicory, and plantain) or do a winter-killed cool-season annual crop (like oats, radishes, and spring peas) for quick fall pasture, and plant the companion perennials the following spring.
8. **Manage the stand carefully** once the companions are established. I like to take the very first harvest as hay. (Although I don't really like to harvest hay at all, I make an exception in the case of a new forage stand.) Haying provides some control of unpalatable broadleaf weeds and sets a stubble height below which animals do not like to graze (the ends of the stubble poke their noses). Gamagrass should be rotationally grazed and should not be harvested lower than a stubble height of 8 inches (I prefer 12 inches) during the growing season.

I have seen many unproductive stands of gamagrass, and the one thing all had in common was violation of the 8-inch rule. This is critical. Gamagrass stores reserve carbohydrates in the stem bases, and grazing the bases during the growing season seriously retards regrowth. If you graze to a 12-inch stubble, it will regrow to 30 inches in three weeks. Graze to a 2-inch stubble and it will regrow to 30 inches in three months. That ungrazed stubble need not be wasted; it can be grazed off completely in winter after a hard freeze.

By using these establishment tricks, I believe gamagrass can be easily incorporated into a crop rotation. Once established, it can provide an incredible amount of pasture in the heat of summer, while it promotes more soil improvement than perhaps any other plant adapted to temperate regions. It can live for centuries as a “forever pasture”; or it can be rotated back to grain crops after a decade or so, and a farmer can grow some monster crops following the improvement in soil structure, while establishing another field of gamagrass elsewhere.

Sunflowers in the Grain Rotation

NORTH CENTRAL KANSAS

Acreage of wheat and other small-grain crops has declined in the US in recent years, because their profitability has lagged behind the glory crops of corn and soybeans. Consequently, many farmers have dropped small grains from their crop rotations because they just don't feel they can include a nonprofitable crop in the mix.

This is unfortunate because, as we have seen, there are very real agronomic advantages to adding a small grain to a crop rotation that's otherwise based on summer crops. But to keep a small grain in the mix, we must figure out how to add profit to that year in the rotation.

One approach is to plant a profitable crop after wheat harvest. Since wheat harvest occurs in early summer in most areas, this leaves quite a bit of growing season available for a second crop. The crop should not be soybeans, however, or any other crop that is currently in the rotation. Cover crops seem like a good option agronomically, but unless a farmer has livestock, how can he or she have cash flow? One idea was discovered by accident—or perhaps accident combined with keen observation and a willingness to experiment.

Accidental Innovation

It seems that many innovations start out as accidental discoveries, such as Teflon and vulcanized rubber. Another example was cultivating sunflowers as a cash crop among interseeded cover crops.

Around 2010, farmers in North Central Kansas began planting a cover crop after wheat harvest, multispecies mixtures that contained a fairly high percentage of sunflowers. As the season progressed, the sunflowers in the cover crop looked just as good as the monoculture hybrid sunflowers they had planted in a different field a short distance away. They said to themselves, "What the heck, let's harvest some and see how they do."

To their surprise, the yield of the sunflowers in the cover crop blend was not much lower than the sunflowers in monoculture. But the real surprise was what happened the following year, when the corn they planted after the sunflower/cover crop combination was among the best-yielding around. In fact, during the severe drought of 2011 it was often the only corn in the immediate area that yielded enough to justify being harvested.

Sunflowers have a reputation of "drying out the ground" because of their massive root system; but corn following sunflowers in a combination of cover crops seemed to exhibit much better drought tolerance than any corn around. What was going on?

Sunflower Culture

One reason sunflowers are so well suited to planting with companions is that they grow taller than many cover crops, and the only portion harvested is the head at the very top of the plant. Consequently, the rest of the plant as well as the underlying cover crop both remain largely undamaged by the combine during harvest.

They may dry out the ground around them, not because they extract water, but because they leave so little residue behind after harvest as a mulch. Depending on the species, companion cover crops can solve this problem by providing an ample amount of mulch. Some species benefit the sunflower crop, others benefit the following crop in rotation, and many can do both.

SOLVING PROBLEMS

For example, one of the biggest problems with producing sunflowers is the head moth, whose larvae bore into sunflower seeds and consume them. Head moths are so problematic that one of the standard rules in sunflower-growing areas is “When you see yellow, spray,” meaning that as soon as the bright yellow petals of the sunflowers emerge, it is time to start spraying. This takes care of the head moths but causes many other problems. It also kills the bees and other pollinators, which is a problem in many ways, but as far as the sunflower crop is concerned, cross-pollination by bees or other insects increases seed production by as much as 25 percent.

Sunflower moths fly at night and locate the sunflowers by smell. Including strongly scented flowering cover crops such as buckwheat and mustards can mask the sunflower aroma, as well as attracting many insect predators that can feed on the moths and moth larvae. These flowering species not only help control the head moth, but also attract pollinators to the field.

ADDING BENEFITS

Companions can also be selected to benefit the following crop. Legume crops such as cowpeas, sweet clover, peas, or vetch can fix nitrogen for the next crop. Deep taprooted crops can bore holes in the soil for roots to follow, while fibrous-rooted crops can loosen the topsoil and increase aggregation. Crops with persistent residue such as oats or flax can provide a moisture-conserving mulch. Buckwheat can free up unavailable forms of phosphorus and render them available to the next crop. Many cover crop species are also capable of providing pasture after the sunflowers have been harvested.

Since this practice has become popularized, many farmers have started playing with companion crops in sunflowers planted after wheat, trying to refine the system. They have tried out different planting schemes, such as planting all the crops together in a grain drill. Or they plant the sunflowers by themselves with a planter for better seed spacing and placement, then follow the planter by seeding in the cover crops. They also vary the timing of

the second planting from immediately after sunflower planting to as much as three weeks later.

This system has a lot of moving parts, and we are still learning which species and practices work best, but there is no doubt that it has considerable potential. By adding cover crops to sunflowers, multiple agronomic goals can be achieved, not the least of which is having a profitable crop option for planting right after wheat harvest to make the year of wheat or other small grains in the rotation profitable.

CHAPTER 9 SUMMARY

- Keep the soil covered at all times. An uncovered soil will become hot enough in summer to kill microbes, will have high rates of evaporation and poor rainfall infiltration, and will be prone to soil erosion.
- Have minimal or no fallow periods. Fallow starves soil microbes of needed root exudates and is a waste of sunlight.
- Rotate different plant families. This will minimize problems of diseases, insects, and nematodes and provide the soil organisms with varied root exudates.
- Capitalize on legumes as a nitrogen source. This is often more economical than using nitrogen fertilizer and has many other advantages to the soil and plant, as described in the chapter on soil minerals.
- Rotate plants with different life cycles. This helps maintain a continual ground cover, efficient capture of sunlight, and continual flow of root exudates. It can also be valuable for reducing weed competition.
- Rotate crops normally planted in wide rows with those grown in narrow rows, since too many crops in succession in wide rows will leave soil prone to erosion.

- A rotation should be at least three years in length, since it takes a minimum of two years for most crop-pathogenic fungi, bacteria, and nematodes to dissipate from a host crop.
- Incorporate livestock grazing, because the microbial conversion of plant material into soil organic matter occurs far more efficiently if the initial fermentation takes place inside an animal's digestive system rather than on the soil surface.

10

Cover Crops

To many farmers, the idea of cover cropping seems ludicrous. When I was an agronomist for a major agribusiness firm, my supervisor once asked me what I was spending my time on. I told him I was mostly doing talks on cover crops because that is what farmers were interested in and were requesting. He asked me what a cover crop was. I explained that it is a crop grown not for harvest but for soil improvement. He said, "That's stupid! Why would anyone do that?" A month later, my job was eliminated.

Cover Crop Benefits

That was in 2011. Apparently, I was ahead of my time because since then cover crops have become one of the hottest topics in agriculture. Still, there are many who haven't seen the light.

Much of the resistance to this practice comes from people in drier areas, concerned that cover crops use moisture, which is true; but so does bare ground. If bare ground stored soil moisture effectively, a lake would be sitting on top of every dirt road in the country—but, in fact, a dirt road dries out far more quickly after a rain than a soil with residue on it. Cover crops can take up moisture, but they can also create a soil condition that is more moisture efficient.

The creation of a moisture-efficient soil is one of the most important reasons to cover-crop, yet it's far from the only one.

The following are many other benefits of the practice, and I suspect that there are even more.

REDUCING SOIL EROSION

The original purpose of cover crops was to reduce soil erosion, and for this they are very effective. They do this through many mechanisms.

- The primary one is providing a covering over the soil surface that absorbs raindrop impact, preventing the rain from dislodging and breaking apart soil aggregates into smaller and more easily moved particles.
- Cover-crop roots also tend to physically bind soil together, and the surface residue provided by either growing cover crops or leaving dead cover crops as mulch slows the velocity of running water tremendously.
- Finally, the root exudates and residue of cover crops feed many organisms that produce biological glues that then increase the formation of soil aggregates and improve their stability. This increases the soil's resistance to erosion, since large particles are more resistant to erosion than small particles are.

INCREASING INFILTRATION OF RAINWATER

The absorption of raindrop impact by either live plants or their dead residue keeps the soil particles from being broken into small particles, which would otherwise form a crust preventing movement of rainwater into lower soil layers. This

protective cover maintains soil porosity. It also slows runoff of rainwater, allowing it time to soak in.

REDUCING EVAPORATION OF SOIL MOISTURE

The mulch created by dead cover-crop residue can greatly reduce the loss of soil moisture by evaporation. Conditions that increase evaporation are sunlight falling on bare soil, bare soil being exposed to wind, and increased soil temperatures. A mulch prevents all of these conditions.

INCREASING SOIL ORGANIC MATTER

The residue left from cover crops adds to the pool of decaying organic residue left by cash crops. In addition, because cover crops are usually terminated while in a vegetative state and still high in protein, they provide more nutrition to soil microbes than the low-protein residue typical of rotations that don't include cover crops. The high-protein cover-crop residue can also blend with the low-protein residue to balance the carbon-nitrogen ratio and create more stable organic matter than would be created from the crop residue alone.

INCREASING MICROBE ACTIVITY

The greatest contribution to soil organic matter from cover crops is not from the residue, however, but from the microbes that feed on root exudates from the cover crops. Even if the cover-crop growth seems unimpressive when viewed from above the soil surface, the roots may be much more substantial. One analysis (by R.B. Jackson et al.; see For Further

Reference) found that, on average, less than 10 percent of the carbon in aboveground plant material became long-term soil organic matter, while 46 percent of the carbon in roots and root exudates did.

ABOVE: *The soil clinging to the roots is called a rhizosheath and is indicative of an active and healthy soil biology. Microbes produce biological glues that aggregate soil particles and bind them to the roots.*

MODIFYING SOIL TEMPERATURE

Whether live or dead, a cover crop acts as an insulating barrier that buffers soil temperature change. A mulch or growing crop

keeps soil warmer in winter by retaining the earth's natural heat, and it keeps soil cooler in summer by preventing sunlight from falling on bare soil. In addition, a cover-cropped soil undergoes less fluctuation in soil temperature from day to night, which can greatly reduce winterkill of crops that live through the winter, such as winter wheat or perennial crops. Microbes also benefit from a stable soil temperature.

ABOVE: *FROM LEFT TO RIGHT: Air temperature, Temperature of covered soil, Temperature of bare soil*

IMPROVING SOIL AERATION

Cover crops prevent crusting from raindrop impact to preserve soil aggregates at the surface, form root channels that act as large pores in surface contact when the roots decay, and feed soil animals such as earthworms that can form large channels.

IMPROVING SOIL AGGREGATION

The residue and root exudates of cover crops feed the microbes that form the biological glues that hold aggregates together.

Cover crops can also maintain populations of mycorrhizal fungi that produce the powerful soil-aggregating agent glomalin (see Chapter 5).

SUPPLEMENTAL LIVESTOCK GRAZING

Most perennial pastures are at their peak production during spring and early summer. Cover crops can be selected to provide grazing during periods when perennial pastures are either not productive or not nutritious. This can improve animal performance, lengthen the grazing season, allow for an increase in animal numbers from the same land area, and reduce need for expensive supplemental feed (hay, grain, silage).

BOOSTING NITROGEN, PHOSPHORUS, AND IRON

See Chapter 6 for a full discussion of how cover crops make nitrogen, phosphorus, and iron more available.

SUPPRESSING DISEASE

Cover crops produce an abundance of decaying residue and root exudates that fuel the growth of microbes. In turn, an array of beneficial nematodes and protozoans then consume not only those benign microbes but also a variety of pathogenic organisms that attack plant roots. Many of the microbes that grow on residue and root exudates also produce natural antibiotics that suppress other organisms, including pathogens. These two mechanisms help suppress soilborne diseases in biologically active soils.

Residue-borne diseases can also be suppressed, because cover crops stimulate the growth of **saprophytic** organisms (organisms that eat dead plant material). These speed the decay of the residue until it becomes a poor host for the disease organisms.

One example of this is the reduction of Goss's wilt in corn by a rye cover crop. The rye grows above the corn residue, and when the foliage wilts during the winter it forms a cover that protects the underlying residue from ultraviolet light (which is deadly to most microbes). It spills high-protein cell contents on the low-protein corn residue, nourishing saprophytic bacteria that rapidly decompose the corn residue, and consume the bacteria that causes the Goss's wilt as well.

A Banquet for Microbes

Cover crops enhance a number of processes that make other mineral nutrients more available. The primary mechanism, however, is nutrient absorption and conversion into organic compounds that become part of the food chain for microbes. Microbes then release those nutrients during the warm, moist conditions that favor plant growth. The result is that nutrient release and nutrient demand are in synchrony.

SUPPRESSING PATHOGENIC NEMATODES

Some cover crops can produce compounds that are toxic to root-attacking nematodes. For example, many species of mustards produce glucosinolates, which become volatile in the soil and act as a "biofumigant," killing parasitic nematodes.

Mustard varieties have been bred for the sole purpose of suppressing various species of nematodes, particularly those that attack crops in which the underground part is harvested, such as potatoes and sugar beets.

Sunn hemp has been shown to be suppressive of soybean cyst nematodes as well as several species of root knot nematodes. Sorghum-sudan produces a compound that is toxic to potato-attacking nematodes when the sorghum residue is incorporated into the soil with tillage.

REDUCING SOIL COMPACTION AND IMPROVING CROP ROOT DEPTH

For decades, farmers tried to deal with compaction by mechanical means, and it just seemed to get worse and worse every year, because it did get worse every year, and unfortunately that was because of what we were trying to do to eliminate it. Our "solutions" to compaction were actually making it worse.

The "tillage radish" was a novel answer to an old problem, and it worked. Those powerful roots bored holes through hardpans, and the roots of the following crops were then able to bore deeper to access more water and more nutrients. Then we learned that mixtures of radishes with other crops with different root systems actually worked better than radishes alone, and the cover crop revolution was born (or at least

rediscovered, since cover crops were common practice prior to the advent of "modern agriculture" using synthetic fertilizers).

LEARNING BY DOING

Meet "Mr. Radish"

When I was working as an agronomist for a large seed company a decade or so back, a big part of my job was putting on meetings for farmers. I would give a typical hour-long presentation on corn, soybeans, herbicides, and all sorts of traditional farming topics. At the end I'd show a handful of slides on various new ideas. One was a picture of a "tillage radish," and I explained that this was a potential solution to soil compaction.

After the presentation, the farmers would surround me, asking me questions—not about the 30 slides I showed on corn, or the 30 slides on soybeans, or the 30 slides I showed on herbicides, insecticides, fungicides, adjuvants, and all other sprayable products. They wanted to know about that radish. It spurred more curiosity than the entire rest of my presentation, and the main question was, "How can we get hold of it to plant?"

So I went on a scavenger hunt for some seed for my company to sell. As with all outside-the-box ideas, this one was met within the company by a huge amount of eye rolls, people elbowing one another, smirks, and ridicule. What

an idea, that a simple plant could fix soil compaction better than some product in a jug!

That first year we sold about 1,200 pounds of radish seed, and within the company I became tagged with the nickname “Mr. Radish.” I have to tell you, that moniker was definitely an icebreaker at company gatherings when people I met wanted to know what it was about.

Fast-forward to today. The little family-owned cover-crop seed company I now work for (Green Cover Seed) sells about a half-million pounds of radish seed a year, in addition to about 20 million pounds of other cover-crop seeds, all of which originally stemmed from a desire among farmers to deal with soil compaction.

A few years later, I was sitting in a seed dealer's office near my farm, and a farmer walked in carrying two soybean plants. One plant had a very long taproot, the other very short. This farmer was farming some land that I had farmed two years before on a one-year deal, and on which I had planted an annual pasture mixture with a healthy dose of radishes. He showed the two soybean plants to the seed dealer and angrily pointed out that seed for the short-rooted soybeans were purchased from him, and that the soybeans with the huge taproot were purchased from a competitor seed company.

I asked where he got that long-rooted soybean, and he told me which field. I then asked, “You mean that farm where I grew radishes two years ago?” His jaw dropped, and he

was speechless for a bit. Then the seed dealer asked if he would kindly plant all the seed purchased from his company on fields that had recently grown radishes.

That farmer has seen the light and is now planting his own radishes. Cover crops can definitely fix compaction, but it is not just about using big taproots to physically bore holes through plowpans, important as that act may be; it is about feeding the soil microbes that create stable soil aggregates.

Design Your Own Cover Crop Blend

GREEN COVER SEED'S SMARTMIX

Putting together a multispecies cover-crop blend can be daunting for a novice. There are hundreds of available species, and sometimes hundreds of varieties of each of those species, and each has particular advantages and disadvantages and different requirements for successful growth, including optimal planting dates.

Working with an experienced cover-crop agronomist is useful, obviously, but lacking that, there is an online cover-crop planning tool called SmartMix, from the cover-crop seed company Green Cover Seed, based in Bladen, Nebraska. SmartMix has an online tutorial program that is very interactive and allows the user to input details such as zip code, seeding method, next cash crop, acres, seeding date, termination date, and up to three goals for the mix. The more than 3 million data points in SmartMix will factor in annual precipitation, first and last freeze dates, growing degree days, projected irrigation, and plant hardiness zone for the selected zip code.

The program gives suitability ratings for more than 100 cover-crop species based on goals, planting dates, and geographic location; mix ratings for C:N ratio, nitrogen

fixation, grazing suitability, frost tolerance, winter hardiness, salinity tolerance, and diversity are also calculated. The cost of the mix is also calculated and shown in real time. Information sheets about each species are available on the website along with in-the-field YouTube videos on when and why to use each species.

For more information, see For Further Reference.

SUPPRESSING WEEDS

Cover crops can suppress weeds in many ways:

Simple competition

Many cover crops are large-seeded, with excellent seedling vigor, and can emerge and form a canopy that deprives the smaller-seeded (and thus slower to emerge) weed seedlings of sunlight.

Creation of a thick mulch

Many small-seeded weed species, such as Palmer amaranth and marestail, have very little energy stored in their seed. This means that a seedling must reach sunlight soon after germination or it will starve. A mulch that's 1 inch thick can provide almost complete control of some weeds.

Allelopathy

In this process, plants produce chemical substances that can negatively affect other plants. The most famous of these allelopathic compounds is the juglone produced by black walnut trees. Most gardeners in the eastern United States have learned the hard way about the poor growth of many plants, particularly tomatoes and other nightshades, in the vicinity of black walnut trees.

Many cover crops produce similar allelopathic compounds. Rye is a notable example. Rye contains three known allelopathic chemicals that are highly effective at reducing the growth of several weeds, including members of the pigweed (amaranth) family and marestail. Sorghums contain an allelopathic compound called sorgoleone.

Manipulation of nitrogen availability

Many weed species prefer nitrogen in the nitrate form. High-nitrogen-demanding cover crops, such as sorghum-sudan or rye, can take up nitrate and sequester it into organic compounds in their structure, thereby making it unavailable to weeds. Of course, this also means nitrogen is unavailable to crops as well—but this situation can be managed so that the crops still yield well. If the next crop is a legume, such as soybeans or peas, then low-nitrogen availability is not an issue because the legume can simply produce its own nitrogen.

If the following cash crop is not a legume but rather a high-nitrogen-demanding crop such as corn, then obviously using a prior high-nitrogen-demanding cover crop is not desirable. But this does not mean that cover crops cannot provide weed control prior to a nitrogen-demanding crop. A legume cover

crop can be grown prior to the cash crop. Although legumes produce nitrogen, this nitrogen is in the form of protein, not in a form immediately available to plants. The protein will convert into plant-available forms upon decay, at which time it can feed the crop.

The nitrogen needs of the cash crop can be met prior to that time by applying a small amount of nitrogen fertilizer in an in-furrow or 2 2 starter application (2 inches to the side and 2 inches below the seed, to prevent the fertilizer from burning the seed). By the time the nitrogen in the decaying cover crop becomes available to both crop and weeds, the crop will have grown well above the weed seedlings and formed a canopy to shade them out.

SUPPORTING WILDLIFE

Bare ground has no benefit to wildlife, while cover crops can be selected to provide both food and cover for almost any species of wildlife. In fact, most of the species used for cover-crop purposes are also commonly used in wildlife food plots. Some provide high-protein foliage for foliage-eating wildlife like deer or elk at any time of the season; seed-producing cover crops can attract seed-eating animals, such as pheasant or bobwhite quail. (See Figure 10.1.)

Other cover crops are highly attractive to insects, which in turn feed insect-eating animals. The newly hatched chicks of many upland bird species require high-protein diets, and these needs are met through soft-bodied insects like hairless caterpillars and aphids. Cover crops that attract these species

are particularly valuable for improving these birds' populations.

LEARNING BY DOING

A Pheasant Surprise

My first attempt at no-tilling soybeans into a rye cover crop was quite the experience. It was really fun and exciting to watch the tractor knock down the tall stalks as I drove through them, and I marveled at how dust-free the operation was compared to the dusty and miserable experience every previous planting operation had been for me.

But what had the most impact on me was just how many hen pheasants I flushed out of that field. Twenty-nine hens on just forty acres. Looking at the surrounding fields, I could easily see why they were in this field: The other fields were completely bare. That summer, I found many nests in the flattened rye residue, and that fall I counted more than a hundred pheasants in a single flush.

Other cover-crop species can provide wildlife with much needed cover in winter or protection from predators. Tall-growing plants like sorghums can make a dense, insulating cover for winter protection. Other plants, such as sunflower,

can create an overhead canopy that offers protection for game birds from avian predators such as hawks, as well as producing high-protein seed.

ATTRACTING BENEFICIAL INSECTS AND ARACHNIDS

Every plant is eaten by a host of insects. Some feed on the leaves, some suck sap, some consume the pollen or nectar. Planting a diverse mix of cover crops is a way to attract a diverse mixture of insects that are in turn eaten by other insects and arachnids, such as lady beetles, mantids, syrphid flies, lacewings, and spiders.

These predators are examples of generalist feeders, in that they eat many species of pests, not just a single species. Lady beetles, for example, are voracious aphid predators, but they don't seem picky about the species of aphid they choose to eat.

Example: Buckwheat as a Bulwark against Aphids

Many of these predators can also substitute protein-rich pollen if their preferred prey species are not present, a fact that some observant farmers have taken advantage of. A relatively new pest in sorghum-producing areas, the sugarcane aphid, has been devastating. Not only does this species suck the sap out of sorghum plants, dramatically reducing yield, but it also excretes excess sugar into honeydew globs and deposits them on the plant. The result

is that the plants become sticky and gummy, and the grain will not pass through a combine during harvest, plugging things up.

Sugarcane aphids also seem resistant to most insecticides, except the newest and most expensive ones. In addition, since aphids reproduce so rapidly, even if the first spray kills 99 percent of them, the survivors will rapidly reproduce into damaging numbers again. It is quite common for farmers to spend $50 an acre on two sprays for sugarcane aphid. Remember, sorghum tends to be grown in marginal acres where corn does not thrive; the economics of these marginal acres do not support that kind of expense.

Some innovative farmers began to combat this pest by interplanting rapidly blooming plants such as buckwheat among their sorghum. The buckwheat blooms very quickly after planting and produces copious amounts of pollen and nectar that attract lady beetles, lacewings, and syrphid flies—all effective aphid predators that can subsist on pollen in the absence of aphids. This allows their numbers to build. When the sugarcane aphid shows up in late summer, there is already a host of predators waiting for them.

Farmers using this approach usually have some sugarcane aphids, but rarely does the population approach sprayable levels, as it is held in check by the predators. A couple of dollars per acre spent for

buckwheat seed is far cheaper than two sprays of cutting-edge insecticide.

IMPROVING SOIL BIOLOGY

Ultimately, all animal life obtains energy from the plants that share that ecosystem. The animals in the soil are no different. Earthworms, insects, termites, spiders, millipedes, and thousands of other soil animals derive nutrition from the plants growing above them.

What happens when there is no plant growth for months on end? These organisms starve and become functionally extinct. All too often the common reaction is "Who cares about a few bugs?" The answer is that we all should care. Each of those organisms has a role to play in the creation and maintenance of a healthy, functioning soil.

Do you ever wonder why natural ecosystems produce luxuriant plant growth without fertilizer input, and our cropland for the most part does not? Perhaps it is partially because of the lack of soil animals to recycle mineral nutrients from organic debris in our croplands.

Tilled cropland results in low levels of infiltration and high levels of runoff. Soil that is not tilled and has vegetative cover, such as that on the prairie, has high levels of infiltration and low amounts of runoff.

PRODUCING POLLEN AND NECTAR

Our conversion of large areas of wildlands into monocultures of grain crops has made many species of bees and other pollinators become endangered. Wildlands such as natural forests and prairies typically have a diversity of flowering plants providing a sequence of bloom over the course of the growing season. You can select cover crops to bloom within a crop rotation and mimic the natural systems on which the pollinators once depended.

In my area, winter annual legumes such as crimson clover and hairy vetch bloom in early spring. Early-spring-planted covers, like phacelia and spring peas, flower in early summer. Summer species such as cowpeas and sunflowers bloom in late summer.

But pollen may have an additional, most significant role. As discussed in Chapter 4, scientists have identified pollen as one of the most important sources of condensation nuclei for rainfall. Cover crops may do more than make soil better at capturing, retaining, and releasing rainwater; they may actually cause it to rain more!

REDUCING FLOODING

If rainwater goes into the soil, instead of running off, then no water goes downhill to the stream, and there is no flooding. This seems ridiculously easy to understand, but so many people fail to make the connection.

Tilled cropland results in low levels of infiltration and high levels of runoff. Soil that is not tilled and has vegetative cover, such as that on the prairie, has high levels of infiltration and

low amounts of runoff. Cropland that is not tilled and is cover-cropped mimics the prairie and has similarly rapid rates of infiltration.

As cover crops prevent flooding, they prevent soil erosion. When soil moves off the landscape and goes into streams, the sediment fills the streambed and reduces the volume of stream area that is available to hold water. Thus, the same amount of water that used to be “streambank full” is now enough to spill over the banks and cause a flood.

IMPROVING WATER QUALITY

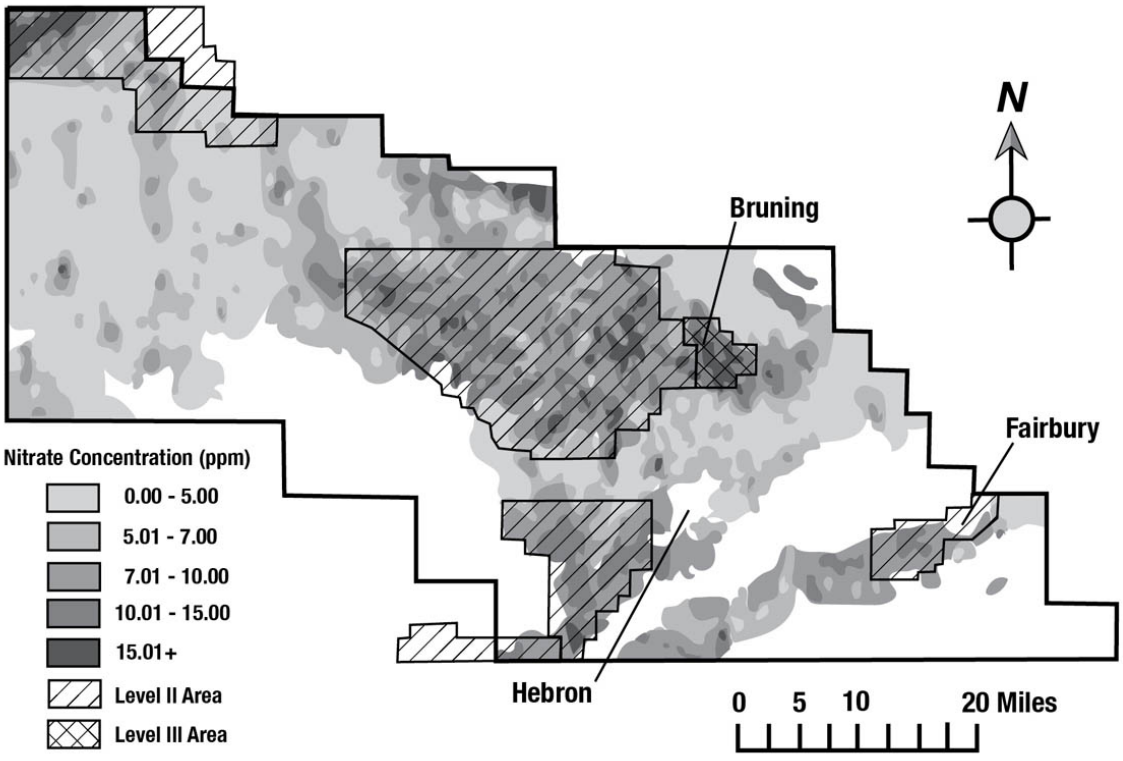
Many pollutants—including plant nutrients such as phosphorus and nitrogen that may become troublesome in excess quantities in water systems, as well as many herbicides such as atrazine—are attached to soil particles that move with soil erosion toward watercourses. By slowing soil erosion, those potential pollutants can be kept out of streams and rivers. This keeps nitrogen and phosphorus out of water where they can cause an accumulation of excess plant nutrients that cause algae to proliferate.

Algae in moderation are a good thing, as algae are the basis for almost all aquatic food chains. But a problem occurs when algae reach extreme quantities and this mass of algal growth suddenly lives out its life cycle and dies off all at once. The microbes that are decaying the algae use up all the oxygen in the water and cause the death of all aerobic organisms in the water, including fish and shellfish.

This is the cause of the fish kills often seen a few weeks after spring rainfall washes recently applied fertilizer off the

soil surface and into streams and rivers. This phenomenon is also the cause of the hypoxic (low oxygen) zones at the mouths of many rivers, including a very large one in the Gulf of Mexico where all the fertilizer that runs off the farms in the Corn Belt and Mississippi delta region end up.

Little Blue NRD Nitrate Sampling Results 2011–2016



ABOVE: *Many wells in irrigated cropland areas test dangerously high in nitrate, well above the standard of 10 ppm. Used courtesy of Little Blue Natural Resources District, Nebraska (littlebluenrd.org).*

The Nitrate Threat—and How to Resolve It

Nitrogen has an additional problem when it comes to water quality. One of the forms of soil nitrogen, nitrate, is a form of nitrogen that does not bind to soil colloids and will move with water through and below the root system, especially when there are no active root systems in the soil to take that nitrate up.

This is a problem in two ways: First, nitrate is a plant nutrient, one that a lot of money is spent on for crops. Nitrate that leaches below the root zone is a valuable commodity that is lost. Second, although it is a natural and valuable plant nutrient, nitrate can be converted into potentially toxic compounds in drinking water, for either humans or animals. That means that if it leaches far enough nitrate can make its way into groundwater systems, and this groundwater can be a health hazard.

In Nebraska, just across the border from where I live in Kansas, there are places where the groundwater has more than five times the level of nitrate deemed safe by the Environmental Protection Agency. This is a consequence of too many years of raising heavily fertilized and irrigated corn on sandy soil. Farmers in these areas are now facing legal restrictions on how much fertilizer and irrigation water they can apply to their crop.

But there is another solution. Cover crops, such as cereal rye grown over the winter between corn crops, can take up nitrate that was unused by the corn crop, change it into organic compounds such as protein that are not susceptible to leaching, and keep it in the top soil layers where it can be

broken down by microbes and made available later for a future corn crop.

LEARNING BY DOING

The Rubber-Boot Test

Farming is all about timeliness. Being unable to plant, spray, or harvest in a timely manner costs a lot in potential crop yield and profit. When I first started my career, I had a summer job field-scouting in southern Nebraska. A third of our customers were no-till, a third were conventional tillage, and a third somewhere in between.

The first two years I scouted were the extremely wet summers of 1992 and 1993. The tilled fields were quagmires in which our rubber boots would sink so deep we could barely walk. On the no-till fields, we could walk across without sinking in. The no-till farmers were able to use the brief periods when it did not rain to get planting and spraying done in a timely fashion.

Memorably (for me), the tilled farmers got nothing done that summer.

IMPROVING SOIL-BEARING STRENGTH

One of the frustrations of farming is the inability to perform needed field operations in a timely manner. Tilled, bare soil simply turns into a muddy quagmire when it rains, and it cannot support the weight of tractors or other vehicles without forming ruts. Soil that is no-tilled and cover-cropped forms a solid turf that can hold up equipment during wet weather. The roots from cover crops add to soil strength, and the residue of cover crops has a "snowshoe" effect to spread the weight of equipment over a larger area. Cover crops can also help prevent livestock from pugging the soil when grazing crop residue.

No-till alone increases the bearing strength of soil, but when it's combined with a cover crop you can get a mat of residue and dense root system that makes the fields even more capable of supporting equipment.

INCREASING ENJOYMENT OF FARMING

This may be the most important benefit of all. As I write this, farming has the highest suicide rate of any occupation in the US. Farming, as it has evolved in this country, has become a game of high-stakes gambling with massive input costs, high levels of risks beyond the farmers' control, and long hours of work—only to see most of the profit in the food production chain handed over to people beyond the farm gate.

Many things can contribute to unhappiness on the farm, but the most significant is financial stress caused by high input costs and low returns. Cover crops can reduce the former (particularly for fertilizers, weed control, and supplemental livestock feed) and increase the latter through increased livestock production and crop yields.

In addition to financial stress, farmers suffer from a sense of helplessness and hopelessness. With tillage and fallow, soil gets worse every year. It is hard to have hope when the basis for all your production (your soil) gets worse every year. No-till and cover crops offer a way farmers can see their soil productivity improve each and every year, building hope for the future. Cover crops give farmers a tool to gain control over their situation and their future.

THE GOOD LIFE VIA COVER CROPPING

Other psychological benefits cover crops can provide are more subtle. Think about facing this reality: your home and livelihood being destroyed by floods nearly every year. Gullied fields with newly planted crops being washed away after a big rain. Those same crops suffering from drought even though it rained a few weeks earlier. Crop fields being overtaken with a weed resistant to the expensive herbicide you just applied. An insect pest infestation popping up after you just sprayed your field for another insect a month before. Crops ravaged by diseases. Overgrazed pastures and nowhere else to put the animals. The daily grind and expense of hauling feed to hungry livestock when there is no pasture available. Crop fields that are bare and brown most of the year, blowing dust when it is dry and so muddy after it does

rain that you can't walk across it without having your boots pulled off your feet, let alone drive anywhere.

No wonder so many farmers are depressed; who wouldn't be in that environment?

Contrast this to the same farm after cover cropping. The soil doesn't wash away after a big rain; it remains in place. The water runs into the soil and gets stored there by the higher organic matter and the mulch, so the crop will not suffer from drought later when the rain stops. This water now goes into the soil, instead of running off into the streams, and thus does not cause flooding.

The streams rise gradually and moderately after rains and now run clear. Fish inhabit the streams because their eggs hatch instead of being covered in mud after every rain, and the abundant insects produced on the landscape wash into the streams to feed the fish in the place of mud.

The day after a rain, the fields are full of earthworms that supply bait for the day-after-it-rained fishing excursion with the kids or grandkids. You can now walk to the stream across fields that are green and covered in flowers. The flowers are visited by flitting butterflies and buzzing bees. The field is full of insects (the vast majority of them benign) that feed the many insect predators waiting to devour any potential insect pests.

Fed by the insects, meadowlarks sing from the fence posts and dragonflies hover overhead. An army of beneficial microbes fed by cover-crop residue and root exudates works belowground to promote organisms that keep crop disease at bay.

When the wind blows, your nose is filled with the aroma of green vegetation and nectar instead of dust. A walk on the farm in fall is interrupted by flushes of pheasant and quail. Winter days are spent watching livestock grazing on cover crops both green and brown, instead of fighting mud and cold all day to haul hay. What a pleasant place to work and live we can create! How much more enjoyable does the cover-cropped farm sound compared to the farm without the cover crops?

Farmers in their seventies tell me that they have gained a new lease on life after they began cover cropping, and they feel a new level of excitement and optimism they have not known for years. They can't wait to see how all the new species in their cover crop blend develop. They love to dig in their field to see how many nitrogen-fixing nodules are on the legume roots and how deep the radish roots go and how many earthworms they can find in a single shovelful.

Cover-cropping makes farming fun again.

Species of Cover Crops and Their Uses

Not all cover crops are created equal. Some plants just work better for some purposes but are inferior for others. Below is a description of several cover crop species that are used around the world.

Cool-Season Annual Grasses

RYE

Rye is probably the most widely used cover crop in the US, and for good reason. It is easy to establish on even very inhospitable soils, including very sandy soils, and it has a tremendous root system that improves soil aggregation. It grows at lower temperatures than any other commonly grown crop and can be successful even when planted very late in the fall after the harvest of corn, cotton, or soybeans. Rye can be planted from late summer through winter; I like to tell people in Kansas and Nebraska that you can plant rye on Christmas and still have acceptable results come spring. It is extremely winter hardy, with some varieties hardy to –80°F (–62°C), and famous for its ability to provide green pasture earlier in spring than any other annual plant, helping shorten the period when ranchers need to feed expensive hay.

Rye is also renowned for its ability to suppress weed growth, most evident on marestail and pigweeds, including Palmer amaranth and common water hemp. Since most of these

populations now exhibit resistance to glyphosate and many other herbicides, this weed suppression ability is highly useful. Rye has an amazing ability to extract a lot of nitrogen out of the soil during the winter, making it an ideal plant for preventing the leaching of nitrate into groundwater following a heavily fertilized crop such as corn.

One objection to more widespread use of rye is that it can be a difficult weed to control in wheat. Clearfield™ varieties of wheat have been developed with tolerance to the herbicide imazamox, an herbicide that can be used to control volunteer rye in wheat.

Triticale

Triticale is a cross between wheat and rye and shares most of its two parents' characteristics, although it exhibits a good degree of hybrid vigor and in some respects excels both its parents, such as with total plant biomass. Originally bred as a grain crop in areas too far north for winter wheat to survive, it offers the winter hardiness of rye and the baking qualities of wheat. In the end it was no more winter hardy than wheat, and not close to wheat in baking quality, but the plants produced an impressive amount of forage of very good quality.

Modern varieties of triticale are widely used as a winter annual forage and cover crop for situations similar to those that rye is used for, and for some purposes they are superior to rye. Compared to rye, triticale is not as easy to grow on the most difficult soils, it is less winter hardy, it does not grow as well at low temperatures, and it is not as effective at suppressing weeds. On the other hand, triticale produces more total biomass

than rye (though not so early), and that biomass has better forage quality and maintains quality better into maturity than rye, especially if a beardless variety of triticale is used.

Triticale is preferred over rye when grazing persists longer into the spring, when the forage is mechanically harvested for hay or silage, or when volunteer rye is a concern in future or adjacent wheat crops. Triticale also comes in spring varieties, which can outyield spring varieties of oats and barley in terms of total biomass. It also has better weed-suppression characteristics than barley or oats.

OATS

Oats are a most versatile cover crop. Spring oats can be planted in early spring for mulch, pasture, hay, or silage, in addition to their historical role as a grain crop. They can also be planted in late summer for an outstanding pasture crop for late fall. Spring oats planted in late summer will winterkill when temperatures drop into the lower teens on the Fahrenheit scale, and the dead foliage makes a very nice mulch come early spring that is easy to plant into.

There are also winter-hardy varieties of oats that are adapted to USDA hardiness Zone 8 or higher, and winter oats are used similarly to other winter cereals for pasture. Oats are more palatable than any other cereal grain as forage when both are at similar stages of maturity. Oats are cheap, due to their high seed yield, which also makes them popular.

Black oats are one of the more popular cover crops in South America, and they're gaining popularity in the US. Black oats are

technically a winter oat, hardy to Zone 7, but are widely fall planted farther north than Zone 7 where they can be expected to winterkill; even though they winterkill, the abundant fall growth more than justifies the inclusion in a cover crop mix.

More winter hardy than white oats, black oats produce a denser root growth. They are also finer-stemmed than white oats and offer better regrowth after grazing. The advantages black oats have over white oats in a fall planting are that black oats will not head out and lose forage quality even if they're planted early, and they will grow longer into the winter because of their greater cold tolerance.

BARLEY

Barley is similar to oats and is also available in both winter and spring versions. Barley is more tolerant of high pH and salt than other cereals and is more salt tolerant than most any other annual crop plants. The winter varieties of barley produce more fall growth than other winter cereals. Similar to spring oat, spring barley can produce tremendous fall forage from a late-summer planting or if planted in early spring can provide a nice crop of hay, silage, or pasture in early summer.

This is an ideal cover crop to precede a legume crop (such as soybeans) on soil that is subject to iron deficiency or chlorosis. Barley varieties for forage are preferably beardless varieties. A typical seeding rate for barley is 75 pounds per acre, planted at about 1 inch deep, although thicker plantings are often employed when the intended use is for forage rather than grain or ungrazed cover. Oh yeah, barley grain is also used for animal

feed, and a few folks like it fermented into a beverage (I have heard).

Annual ryegrass is not a cereal grain but is rather more "grass-like." It is not as winter-active as the cereals, but it has better forage quality with a high sugar content, regrows better after grazing, and has a denser root system than the cereals. It also has better tolerance of heavy clay and poor drainage. Annual ryegrass is used extensively as the basis for grass-finishing livestock, as it has a higher energy content than other winter annuals; the meat from ryegrass-finished livestock has a very good flavor.

The plant has an unusual ability to chemically dissolve fragipans (chemically cemented hardpans found in much of the southeastern US). It has been found to take out about 1 inch of fragipan (from the top down) for each year of growth. A pure stand seeding rate of annual ryegrass is about 25 pounds per acre, planted about ¼ inch deep. Ryegrass can be broadcast with good success when rainfall follows seeding.

Warm-Season Grasses

SORGHUMS AND SORGHUM-SUDANS

Hybrids of sorghum and sudangrass, sorghums, and sorghum-sudans produce more biomass per acre than any other annual grass during the heat of summer, and they produce more root mass as well (sorghums produce several times the root mass of corn, for example). Sorghums are usually higher-yielding if they are allowed to grow to full maturity, while sorghum-sudans offer

better forage quality and faster regrowth after grazing. If livestock forage is desired, a brown midrib variety should be selected. Brown midrib is a naturally occurring mutation in which the plant produces less indigestible lignin than do conventional varieties. Photoperiod-sensitive varieties are more water efficient and higher yielding, while brachytic dwarf varieties are leafier and regrow faster after grazing.

Sorghums can produce a toxin called prussic acid that can kill grazing animals. It is concentrated in fresh regrowth and is particularly hazardous in freshly frosted forage. Sorghum residue is very low in protein, like most warm-season grasses, and the decay of the residue can tie up considerable amounts of nitrogen. Therefore, it is advisable to either follow sorghums with a legume crop or add additional sources of nitrogen fertility prior to the next crop. Sorghums are very drought tolerant but are susceptible to iron deficiency chlorosis on calcareous soils (high-pH soils with excess calcium carbonate). Sorghums should not be fed to horses.

MILLETS

Pearl millet is usually the most productive millet. It is almost as productive as sorghum-sudan and has an additional advantage of being free of prussic acid. Thus, it finds favor in many grazing situations. It is more tolerant of high-pH and sandy soils. It is also available in brown midrib varieties. Dwarf varieties are leafier and regrow better after grazing than taller hybrids.

Japanese millet is a relative of the weedy barnyard grass but is much more productive and more palatable to grazing livestock.

Like barnyard grass, it is very tolerant of flooding and is a good addition to mixtures for fields with drainage issues. It is not as productive as pearl millet but usually more productive than other millets. It is a good seed producer and is a favorite food of many duck species as well as upland game birds.

Foxtail millet is a fast-growing grass with very fine stems that make it dry rapidly after mowing and very easy to put up for hay. However, it has a short maturity, which makes it lower yielding than pearl millet. Foxtail millet's best value is for producing a quick hay crop, although it should not be fed to horses, as it can cause cystitis issues in the joints. It is also referred to as German millet; a similar variety is 'White Wonder'. As a grazing crop, it is inferior to pearl millet and Japanese millet. Foxtail millet seed is usually very inexpensive.

Teff is a very fine-stemmed grass that dries out rapidly after mowing (even faster than foxtail millet) and is often cured the day after mowing. Due to this rapid drying, it is usually used as a hay crop rather than as a cover crop. It has very small seeds that establish easily after broadcasting prior to a rain. Teff is often broadcast into hailed-out cornfields to provide additional pasture or hay when the hail damage is severe enough that a forage harvest is preferable to a grain harvest.

Crabgrass is usually considered a common weed, but it has several advantages as a cover crop or forage crop. It grows rapidly, makes nutritious pasture, and can be established by broadcasting. It also reseeds readily, for better or worse. It is best used on areas that will be used for pasturing every year,

rather than in rotation with grain crops, due to its competitiveness with crops. Crabgrass plants increase in size as the season progresses, compensating for other plants in the mixture that tend to thin out as the grazing season progresses.

Corn is usually produced as a grain crop, but—when you can get the seed for cheap—it also works well as a cover crop because it produces a lot of biomass. During the heat of summer, corn is outyielded by sorghums, but if planting dates are delayed past midsummer, corn will outproduce sorghum due to its better cold tolerance. Brown mid-rib varieties are available and are far more digestible to animals than grain varieties.

Warm-Season Legumes

Sunn hemp produces more biomass and more nitrogen in less time than any other legume. Unlike other legumes, which have residue that decays rapidly and leaves little ground cover, sunn hemp has stalks that are fibrous, hard, woody, and persistent. While this is an advantage to soil-building, it can make planting the next crop difficult, as the fibers tend to wrap around any type of spinning equipment. Sunn hemp also exudes compounds from the roots that are toxic to many parasitic nematodes, including soybean cyst nematode. Sunn hemp is highly palatable to sheep, goats, and deer, but only the variety 'Tropic Sun' is very palatable to cattle.

Cowpeas are a viny legume that makes excellent summer pasture. They fix more nitrogen than soybeans and are more tolerant of heat, drought, and poor soil. Cowpeas are most

productive when planted in a mixture with tall, erect plants to act like a trellis. I really like a blend of sunn hemp and cowpeas as a nitrogen-fixing combination (See Figure 9.3.), although I usually add a few other summer annual species into the blend for diversity and to accomplish other objectives.

Cowpeas will regrow rapidly after grazing, provided the animals are rotationally grazed and allowed to eat just the leaves —and not forced to eat the stems—before they are moved to the next paddock. This keeps the growing points intact, and the leaves will rapidly regrow. Cowpea forage has a bit of an odd odor that causes many livestock to initially avoid consuming it, but once animals try it they will consume it quite readily.

Guar is a legume usually harvested for the mucilaginous seeds, the source of guar gum used as a food additive. If you read a label on a container of ice cream, you will often find that guar gum is a common ingredient. It is not as productive as cowpeas or sunn hemp, but it is very drought tolerant and is one of the few summer annual legumes with tolerance to salty soils.

While green, guar is not very palatable to livestock but becomes palatable upon drying after haymaking or frost. The beans are retained in the pod after maturity, rather than splitting open like most legume pods. This can make guar a valuable component in mixtures with nonheading sorghums used for stockpiled winter grazing, as the beans can provide a good source of protein to complement the low-protein sorghum residue.

Mung beans are similar in nature to cowpeas. They have smaller seed, making them usually much cheaper to plant, and they offer

diversity in a cover-crop blend. Mung beans are earlier in maturity than cowpeas, which limits their yield potential for forage and nitrogen fixation potential compared to the longer-maturing cowpeas. Mung beans are very palatable to grazing livestock.

Forage soybeans are simply soybean varieties that grow much larger than grain varieties. They produce more foliage and more nitrogen than grain varieties and are usually longer in maturity.

Cool-Season Legumes

CLOVERS

Crimson clover is a popular winter annual cover crop in the southeast United States, where it is planted in the fall. In far-northern areas, it is used as a spring-planted clover. It is a good nitrogen fixer, is moderately winter hardy, and is not particularly deep-rooted. One of the first plants to flower in the spring, it is valuable for pollinators. This species is particularly attractive due to its bright red flowers and is often seeded in roadside mixtures for beautification purposes. It makes good pasture for most livestock species, although horses avoid it, which is good because the leaf hairs reputedly cause the formation of hairballs in the horse gut. It has its own specific inoculant species, but this species is commonly added to commercially available "clover inoculant." It does not typically cause bloat.

Balansa clover is gaining popularity in the cover crop world, mainly because of the development of newer varieties such as

'FIXatioN'. It greens up later than crimson clover in the spring but is more winter hardy and provides more palatable forage. Balansa clover has its own specific inoculant. It has large, hollow stems, which make it easier to kill by roller-crimping than crimson clover. It is best suited for crop rotations in which the following crop is planted later in the spring—and the balansa is allowed to grow long enough in the spring to realize its growth potential. Balansa is usually planted in the fall and overwinters.

VETCHES

Hairy vetch is the most winter-hardy winter annual legume, and probably is the best nitrogen fixer as well. It is typically fall-planted. Hairy vetch produces a dense mulch that is an ideal no-till seedbed, and it is easily killed by roller-crimping after bloom. It is not only an excellent nitrogen fixer, but it also contains compounds that suppress the growth of many weed species. It produces nutritious forage that is palatable to most livestock, although horses refuse it.

Occasionally the plant causes a fatal allergic reaction in some cattle, particularly Black Angus and Holstein. The reaction is rare but devastating and gruesome when it occurs, as it can cause severe blistering with large amounts of skin flaking off. The causal agent appears to be not the vetch itself, but a mycotoxin produced by a *Fusarium* fungus that occasionally attacks vetch in hot, humid conditions. Until more is known about vetch toxicity, pasture vetch with caution. Drier areas will likely have fewer problems than humid areas. Vetch seed also has toxic properties, so it is prudent to avoid pasturing vetch after seed set. It is also important to not allow vetch to produce seed if

it is in a crop being harvested for human consumption, such as winter wheat.

Hairy vetch has hard seeds that may emerge years after planting and become a troublesome weed in wheat harvested for grain. This is primarily a problem in organic wheat production, where herbicides are not used; otherwise, it is easily killed by phenoxy herbicides such as 2,4-D and also by sulfonylurea herbicides commonly used in wheat. Hairy vetch is rather tolerant of glyphosate, so glyphosate alone is not sufficient for herbicidal burndown. A variety called 'Villana' is reputed to have a very low hard-seed content (nearly 0 percent), so it might be much more useful in organic crop production if wheat is in the rotation. Other varieties have been selected for much earlier bloom, which allows for earlier kill by roller-crimping.

Common vetch is not as winter hardy as hairy vetch but is a better seed producer, making it cheaper to plant. Since it is less winter hardy, common vetch is fall planted only in warmer regions (Zone 7 or higher) and spring-planted elsewhere, or it is fall-planted in northern regions for a planned winterkill. It is a bit more upright than hairy vetch and not quite so viny. The seeds of common vetch are a bit larger than those of hairy vetch; they are also not as hard as hairy vetch seeds and do not persist as long in the soil. There are also interspecific hybrids of common vetch and hairy vetch.

Chickling vetch is not a true vetch but is instead a member of the sweet pea family. It has exceptional forage quality and has outstanding nitrogen-fixation capability. It is intolerant of competition and does not perform well in mixtures with taller

plants. It also has large irregular seeds (they look like road gravel) that do not flow well through many seed drills. Chickling vetch does not typically cause bloat. It has been researched as a legume to interseed into dormant bermudagrass and has shown excellent promise for this role, providing both pasture during the dormant season of bermudagrass and a sizable nitrogen contribution to the pasture. It can be spring-planted, or it can be fall planted and allowed to winterkill.

Chickpea (garbanzo bean, gram) is usually used as a grain legume for human consumption but is an effective cover-crop species as well, being a good nitrogen fixer. The variety 'Desi' is smaller-seeded and more economical to plant than varieties bred for human consumption.

Lentils are not as productive as many other cool-season legumes but have very good palatability to livestock. Most lentil varieties are intended for grain production, while the variety 'Indianhead' was bred for cover-crop purposes. It has relatively small seeds, so a pound of seed creates more plants than with other varieties. Most lentils are not winter hardy, but winter-hardy varieties are available, such as 'Morton.' Lentils have an open canopy and do not compete well against weeds, but this is an advantage when lentils are used as an interseeding crop into perennial pastures or as a companion crop in newly seeded pastures.

Lupines are somewhat unusual among legumes in that they are not hosts of mycorrhizal fungi. Since they do not benefit from the water and nutrient uptake capability of the mycorrhizae, they

have evolved different mechanisms for nutrient uptake, including phosphate-solubilizing exudates. This mechanism adds diversity to the root exudates produced by a cover crop blend. Sweet lupines are nontoxic to grazing livestock, but bitter lupines contain toxic alkaloids and should not be pastured. Lupines are a cool-season crop that overwinter only in the Deep South. In more northern areas, they are either fall-planted and allowed to winterkill, or they are spring planted. Lupines have a very beautiful flower and are used in ornamental plantings.

Sweet clover is a biennial legume that was once the most popular green manure in the country. It has very deep roots and is an excellent nitrogen fixer, and it has an unusual ability to extract phosphorus and potassium from rather unavailable sources. Sweet clover grows well on highly inhospitable soils, such as very dry and calcareous soils. It produces a large volume of forage that is not particularly liked by livestock because it contains the bitter compound coumarin. Although it is not very palatable, it is nutritious, and animal performance on it is very good.

The plant makes poor hay because its coarse stems cause it to dry slowly, and if it becomes moldy, the coumarin turns into a compound called dicoumarol, which is the ingredient in warfarin, a common rat poison. Dicoumarol antagonizes vitamin K and makes the blood very thin and unable to clot. This is a problem during birthing, dehorning, or castration. Very high intakes of dicoumarol can cause internal hemorrhaging.

As pasture, sweet clover does not pose a dicoumarol risk. Being biennial, it is normally planted in early spring and is usually terminated the following spring. This makes it hard to fit

into crop rotations without sacrificing an entire year of production. Formerly, sweet clover was seeded at the same time as oats, or seeded into a growing crop of winter wheat, and the clover grew slowly under the grain canopy and then rapidly once the grain was removed. However, with today's high levels of nitrogen fertilization for high grain yields, the soil nitrogen level is so high that the clover fails to nodulate and does not grow well.

Organic growers, who do not use synthetic nitrogen fertilizer, still find interseeding sweetclover into wheat a useful practice. The concept of interseeding or using sweet clover as a companion crop is useful even in conventional agriculture, but the species of companion crop may need to be altered. A preferred companion crop for clover would be a short-lived cool-season annual legume, such as spring peas or spring lentils. Since peas and lentils are also legumes, they do not require nitrogen fertilization, and the clover underneath nodulates properly.

There are several species of sweet clover:

- Yellow blossom sweet clover is the most commonly used.
- White blossom sweet clover blooms later and is more productive but requires more time in the field to realize this productivity.
- Hubam is an annual version of sweet clover that blooms in late summer of its first year of growth, if spring planted (as it is in the North); in the South, it is used as a winter annual that is fall planted and blooms the following spring. Hubam sweet clover has some value in cotton-growing regions because it

apparently stimulates the growth of soil microbes antagonistic to cotton root rot.

All sweet clover species are exceptional producers of both pollen and nectar, making them valuable for both wild pollinators and honey production. A mixture of all three species can provide a nearly continuous bloom of nectar and pollen from late spring through frost. Sweet clover is highly sensitive to the herbicide 2,4-D, making it easy to terminate chemically. It is also easy to kill with a close mowing after it blooms, a useful characteristic for organic growers.

A stand of sweet clover has exceptional value for ground-dwelling birds, such as bobwhite quail, if the sweet clover is allowed to remain alive for its second year of growth through the early brooding season of chicks. The tall, coarse structure and attractiveness to soft-bodied insects provides both food and cover for newly hatched ground-dwelling birds such as meadowlarks and quail.

My father used to raise sweet clover for seed, and the seed production fields were a joy to walk through, being fragrant and colorful. They were literally buzzing with the activity of all sorts of bees, and you could hear the movements of hidden wildlife, mostly coveys of quail, as they rustled through the tall, dense canopy.

Arrowleaf clover is a winter annual legume that is more productive but less winter hardy than crimson clover. Its forage is somewhat higher quality than crimson and is more productive but is not so early to green up in the spring. Arrowleaf clover is

high in tannin and does not cause bloat. Most animals find arrowleaf palatable enough for good consumption, but horses do not. It is winter hardy approximately to USDA hardiness Zone 7. In northern areas it can be used as a summer annual.

Peas are a very versatile crop, for grain, forage, or nitrogen fixation. Peas come in spring versions for grain or for forage, and in winter-hardy versions ('Austrian Winter' is the best known, although there are newer and superior varieties). Pea forage is not initially palatable to livestock but is highly nutritious once they become accustomed to it. Curiously, dried pea forage in hay is eagerly eaten, but green forage is often initially refused.

Peas are a good nitrogen fixer and are not deep-rooted but are one of the more drought-tolerant legumes. Both winter peas and spring peas can be fall planted, with the spring peas being expected to winterkill, but making much more fall growth before they do. Spring peas are spring planted if the goal is seed production. They are also often planted in early spring as a companion legume in mixtures with oats or other spring cereal.

Fava beans (also called faba beans) are excellent nitrogen fixers, and their blooms are particularly attractive to many beneficial insects. They are a cool-season crop but are not very winter hardy. The leaves are high in tannin and are not very palatable to livestock. Fava beans are harvested for grain and crop used as human food (made famous by Hannibal Lecter in the movie *The Silence of the Lambs*, as his preferred side dish to the liver of his victims).

Fava bean seeds are large and require a very high seeding rate, making them expensive to use as a cover crop, although

they are perhaps the best nitrogen fixer among cool-season annual legumes. In areas in which they overwinter (hardiness Zones 9 and above) they are fall planted, while in northern areas they are either spring planted or fall planted with the expectation of winterkill. The dead residue of fava beans is dark black, making it highly absorptive of sunlight; fava bean residue warms up early in spring, a bonus for early-planted spring crops that may follow.

Brassicas

Radish (oilseed and forage radishes) is a crop that has probably done more to promote cover cropping than any other species except perhaps rye. The tremendous deep taproots of forage radish (I attended a field day where root activity was detected at a depth of 9 feet) can break up compaction and increase the rooting depth of the following crop. One study indicated that corn following radish had the same root density at 24 inches as corn following fallow had at 8 inches. Radish works best planted about 60 to 75 days prior to average first frost in fall. Radishes are long-day photoperiod-sensitive, so they will bolt and bloom rapidly if spring planted.

Radish is often unpalatable to livestock until the cooler temperatures of fall cause an increase in sugar content. It is highly nutritious, being high in protein, energy, and digestibility. Livestock grazing any brassica in a pure stand are subject to several metabolic disorders, including polioencephalomalacia and a form of emphysema, caused by brassicas' high content of S-methylcysteine oxides (SMCOs) and glucosinolates. These problems are prevented by grazing brassicas in a mixture rather

than in pure stands; animal performance is much better if brassicas are limited to about half the dietary dry matter intake.

It is particularly beneficial to include a warm-season grass such as BMR corn or millet that will provide fiber to the diet after a frost, as brassicas lack adequate fiber for proper rumen function. Radish usually winterkills after several consecutive hours below 18°F (–7.8°C). 'Nitro' radish and smart radishes are traditional forage-type radishes for pasture and for breaking compaction in the fall. The variety 'Graza' is more of a grazing radish that is a very heat-tolerant brassica; it is my top choice (along with collards) as a summer-planted brassica. There are also radish varieties bred more for nematode control, such as 'Defender' and 'Image'.

Turnip might not be the soil improver that radish is, but the palatability of turnip forage is better, and the roots are more accessible to livestock. Because both the tops and roots are eaten, the carrying capacity is very high, but the regrowth is nonexistent. 'Purple Top' is the old standard variety, but there are newer varieties that are bred for either higher root yields or for more foliage that will regrow after grazing. Turnip usually winterkills after several hours below 16°F (8.9°C).

Rapeseed is the "wildest" brassica. It is the same species as the grain crop canola but is bred for forage purposes rather than seed yield. One of the more winter-hardy brassicas, it will survive mild winters when temperatures seldom drop below 0°F (–17.7°C). It is probably the most salt-tolerant brassica, and it regrows after grazing very well. It is also usually the cheapest brassica species to plant.

Kale is the brassica that grows at the coldest temperatures and will survive temperatures down to 10°F (12°C). In 2013 my farm had a 14°F (–10.0°C)–freeze in November, and the radishes and turnips killed out, while the hybrid kale survived. It then warmed up for a month and the kale continued to provide quality grazing while the other brassicas wilted and turned to mush.

Collards are one of the most heat-tolerant brassicas as well as one of the best grazing brassicas. They are very palatable and tolerate midsummer planting better than most brassicas. The regrowth potential of collards after grazing is exceptional, and they will grow later into the fall than most brassicas. For multiple fall grazings, collards are tough to beat.

Mustards are usually used for their nematicidal effects that derive from their content of glucosinolate compounds. Different mustards have been bred to control different nematodes, such as those that attack potatoes and sugar beets. Mustards usually have poor palatability to grazing livestock. Some mustards are useful as table greens, and each variety has a different flavor. Florida broadleaf mustard, for example, has a horseradish flavor. I like to make a sort of horseradish-flavored pesto from broadleaf mustard and put it on steak. It has the same nutritional benefits as kale but tastes sooooo much better.

Broadleaf mustard is also one of the absolute best cover crops for suppressing the growth of cool-season weeds. I think broadleaf mustard may also be useful as a nonchemical, non-tillage method of killing a perennial grass sod, such as bermudagrass or endophyte-infected fescue. Simply plant the mustard while the grass is dormant, so the mustard has a head

start, and let those huge leaves shade out the grass. For those people who want to kill an undesirable sod without having to resort to glyphosate, this may be a good option.

African cabbage (Ethiopian cabbage) differs from other brassicas in that it does not melt away to nothing after winterkilling. It has a woody central stem that remains erect over winter, providing soil protection and trapping snow. It has poor grazing palatability relative to most brassicas but is tasty to humans, with a flavor similar to head cabbages.

Forbs

Buckwheat is an unusual plant. It produces more pollen and nectar than perhaps any other annual plant, and it blooms as early as three weeks after planting. The pollen acts as an alternative food crop to predatory insect larvae, such as lacewings, lady beetles, and syrphid flies. Therefore, it can build populations of these beneficial insects to be ready and waiting in case of an aphid outbreak. I like to include buckwheat in every cover crop mixture that contains plants susceptible to aphid attack, such as sorghums, which are attacked by many species of aphids, including the difficult-to-control sugarcane aphid.

Since it is nonmycorrhizal, buckwheat has evolved compensatory mechanisms to obtain nutrients. It has root exudates that solubilize phosphorus from unavailable forms into available ones. Because of its inability to host mycorrhizal fungi, it is best used in mixtures with mycorrhizal hosts to maintain mycorrhizal populations.

Buckwheat is effective when planted anytime from midspring to late summer. It is often planted to help populations of pollinator insects, and as a plant to feed honeybees. Honeybees feeding on buckwheat produce a dark, strong-flavored honey that some people relish but others find too strong. Buckwheat also produces nectar only in the morning, so other flowering plants should be available to allow bees to gather nectar in the afternoon.

Although it grows in warmer soils (above 55°F [13°C]), buckwheat is also sensitive to excess heat, especially during flowering. Since it blooms so shortly after planting, it can be planted at any time from late spring through late summer and still provide bloom. Buckwheat foliage is not usually eaten by animals when pastured in a mixture, but the mature seed is nutritious and palatable, with a nutritional value similar to oat grain.

Sunflower is a deep-taprooted forb and an excellent mycorrhizal host. It is highly attractive to many beneficial insects, and the seed is valuable to many bird species. Although it is technically a cool-season plant, it does well in the heat of summer. Sunflowers are cheap, and the massive root system does wonders for soil aggregation.

Phacelia is native to the deserts of the American Southwest. It produces both abundant nectar and pollen and is an excellent honey plant, rivaling buckwheat for the title of most nectar and pollen per acre for an annual plant. The roots form a cobweb-like mat at the soil surface, making it highly receptive to rainfall infiltration. *Phacelia* performs best when planted in early spring

or late summer (similar to when alfalfa would be planted), but it blooms only when it is spring planted. *Phacelia* is known to improve availability of potassium.

Okra is best known for its edible seedpods, but it has recently come into use as a cover crop as well. It produces a high amount of biomass, the pods and foliage are relished by livestock, it has a deep taproot, and the stalks are highly lignified, allowing it to provide persistent cover and remain upright in winter to catch snow.

Since it is a member of the mallow family, as is cotton, do not use okra in a crop rotation that also features cotton, since it might harbor insects or diseases that affect cotton. In rotations that do not include cotton, okra offers an added level of diversity, as no other cover crops are from the same family. Okra also is reputed to help control internal parasites of livestock when pastured. It is a heat-loving plant and grows when soil and air temperatures are above 70°F (21°C). It is killed at first frost.

Squash (including pumpkin) is another recent entry into the cover crop arena. It was long used as a companion to corn and pole beans in Native American gardens, where it not only produced edible fruit but smothered the ground for weed control and a mulch effect. The sprawling vines spread to fill in gaps in the canopy and convert otherwise wasted sunlight into vegetation. While squash foliage is not usually eaten by grazing livestock, squash fruit is relished by them, and the seeds have activity against intestinal parasites of livestock. Watching a cow eat a mushy, frozen-and-rethawed pumpkin is quite entertaining, as is watching their manure turn orange a day later. Squash can

harvest summer sunlight and store it as highly nutritious fruit for use in fall grazing.

Watermelons are another plant that can be used in a similar role to squashes and pumpkins—as a vining plant that converts summer sunlight into a feedstuff that can be eaten later. The fruit is not as durable as squash for use in the winter, and it usually ripens earlier in the year; but once your livestock figure out just how good those big oblong green things are inside, there are few things they like to eat as much. No problem picking a few for yourself, either! That is, if you can beat the raccoons, squirrels, coyotes, deer, rabbits, neighbors, and Sasquatches to the fruit.

Every wild creature, it seems, loves watermelons, and they are one of the top deer-attracting plants. Watermelons are usually long gone before hunting season but can be used to encourage deer to visit a location and can be used in conjunction with other plants that will be attractive when hunting season arrives.

Flax is a cool-season annual that is the source of linen fiber, flaxseed, linseed oil, and linseed meal. It offers value as a cover crop due to its excellent ability to host mycorrhizal fungi and to provide persistent residue, which few other cool-season broadleaves will do. Flax stems stay upright in winter to trap snow. Flax has little to no grazing value, but I have customers who include it in mixes so they will have residue left after grazing to protect the soil. Flax also has an almost magical ability to boost yields of the following crop in rotation, an ability usually attributed to its stimulatory effect on soil microbiology.

Safflower is a typically spiny, deep-taprooted forb that produces a seed from which oil is extracted commercially. The spiny nature makes a thick stand of safflower effective as a temporary fence against both livestock and most wildlife, even coyotes and foxes. There are reports of people planting a ring of safflower around their lambing pens to deter predators, and around new fruit trees to protect them from deer and cattle. There is a spineless variety called 'Baldy' that is highly palatable to livestock, particularly after the seedpods are full of high-protein seed. Safflower roots have been found to grow as deep as 9 feet, which explains its ability to grow in very dry regions.

Sugar beets and fodder beets (mangels) are similar to radishes in use but are more tolerant of salty soils and heat. They are chenopods rather than brassicas so they offer some diversity in root exudates and plant compounds. Sugar beets can be high in oxalates; if a diet is nearly pure sugar beets, the oxalates can cause urinary calculi, commonly referred to as "water-belly." The oxalates form sharp crystals that block the urinary tract, a condition similar to kidney stones in humans. A high-calcium mineral supplement can prevent calculi problems, as can simply adding different plants in the mixture.

A blend of sugar beets and brassicas offers a diversity of plants with large taproots and dilutes the antiquality factors found in each; the beets are high in oxalates while brassicas are high in glucosinolates. A blend of both species dilutes the effect of both and reduces the negative impact on animal performance compared to that of a pure stand of either plant alone.

Sugar beets provide excellent pasture of both roots and tops when they are part of a ration, although they should not be pastured as the sole dietary component due to their high oxalate content. They are intolerant of competition and thus tend to get smothered out in mixtures with tall-growing summer annuals, and they work best when planted with slower-developing cool-season plants. Beets are a warm-season plant but are slower to develop than most other warm-season plants, though they are more cold tolerant and can be planted at cooler soil and air temperatures (50°F [10°C]) than most warm-season plants.

RATING COVER CROPS

Summer Legumes

SPECIES	BIOMASS	ROOT	DROUGHT	SHADE	FLOOD	MIN. TEMP.	WINTERKILL	SEED RATE	DEPTH	INOCULANT	N FIX
Cowpeas	M	MT	G	F	P	60	32	40	1	cowpea/ peanut	H
Sunn hemp	H	MT	E	F	P	60	32	20	1	cowpea/ peanut	VH
Mung beans	L–M	MT	G	F	P	60	32	20	.75–1	cowpea/ peanut	M
Soybean	L–M	MT	F	F	F	50	32	60	1	soybean	M
Guar	L–M	DT	E	P	P	60	32	20	.75–1	guar	L–M

Cool-Season Legumes

RATING COVER CROPS

SPECIES	BIOMASS	ROOT	DROUGHT	SHADE	FLOOD	MIN. TEMP.	WINTERKILL	SEED RATE	DEPTH	INOCULANT	N FIX
Hairy vetch	M	MT	G	G	F	40	–30	20	.25–1	pea/vetch	H
Crimson clover	M	ST	F	E	F	40	–15	15	.25–.5	crimson clover	M
Common vetch	M	ST	F	G	F	40	5	20	.25–.75	pea/vetch	M
Winter peas	M	ST	G	G	F	40	0	40	1–3	pea/vetch	M
Spring peas	M	ST	G	G	F	40	16	60	1–3	pea/vetch	M
Sweet clover	H	DT	E	G	P	40	–40	10	.25–.5	alfalfa/ sweet clover	H
Balansa clover	M	MT	F	G	G	40	20	6	.25	balansa	H
Berseem clover	M	MT	F	G	E	40	0	10	.25–.5	true clover	M
Chickling vetch	M	MT	G	P	F	40	15	20	1–2	pea/vetch	H
Fava beans	H	DT	F	F	F	40	20	90	1	pea/vetch	VH

RATING COVER CROPS

CHART VALUES AND RATINGS

Biomass: biomass potential relative to other legumes. L=low, M=moderate, H=high, VH=very high

Root: root depth and type. S=shallow, M=moderate, D=deep, T=taproot, F=fibrous

Drought: drought tolerance. P=poor, F=fair, G=good, E=excellent

Shade: shade tolerance. P=poor, F=fair, G=good, E=excellent

Flood: flood tolerance. P=poor, F=fair, G=good, E=excellent

Min. Temp.: minimum germination temperature in degrees F

Winterkill: temperature in degrees F at which winterkill occurs; varies with variety, snow cover, residue cover, and soil moisture.

Seed rate: recommended seeding rate in pounds per acre

Depth: recommended planting depth in inches

Inoculant: recommended inoculant group

N fix: relative level of nitrogen fixation. L=low, M=medium, H=high, VH=very high

Summer Annual Grasses

SPECIES	BIOMASS	ROOT	DROUGHT	SHADE	FLOOD	MIN. TEMP.	WINTERKILL	SEED RATE	DEPTH
Sorghum-sudan	VH	DF	E	P	F	60	32	25	1
Pearl millet	H	MF	E	P	P	65	32	15	.75
Brown top millet	M	SF	G	P	G	60	32	15	.5–.75
Japanese millet	M	SF	G	P	E	55	32	15	.25–.75
Foxtail millet	M	SF	G	P	P	60	32	15	.5–.75
Teff	M	SF	G	P	P	60	32	8	.15

Winter Annual Grasses

SPECIES	BIOMASS	ROOT	DROUGHT	SHADE	FLOOD	MIN. TEMP.	WINTERKILL	SEED RATE	DEPTH
Annual ryegrass	H	MF	P	G	G	40	-10	20–30	.25–.75
Winter barley	H	MF	G	F	F	45	-10	75–100	.75–2
Spring barley	H	SF	G	F	F	40	15	75–100	.75–2
Rye	H	DF	E	F	F	35	-40	60–100	.5–2
Winter oats	H	SF	F	F	F	45	0	60–90	.75–1.5
Spring oats	H	SF	F	F	F	40	20	60–90	.75–1.5
Spring triticale	VH	MF	G	F	F	40	15	80–100	.75–2
Winter triticale	VH	DF	G	F	F	40	-25	80–100	.75–2

Brassicas

Brassicas

SPECIES	BIOMASS	ROOT	DROUGHT	SHADE	FLOOD	MIN. TEMP.	WINTERKILL	SEED RATE	DEPTH
Mustards	M	MT	M	F	F	40	20	5	.25–.5
Purple Top turnip	M	DT	G	F	F	40	15	5	.25–.5
Radish	M	DT	G	F	F	40	18	8	.5–.75
Collard	M	DT	G	F	F	40	10	5	.25–.5
Rapeseed	M	DT	G	F	F	40	10	5	.25–.5
Kale	M	DT	G	F	F	40	10	5	.25–.5

Forbs

SPECIES	BIOMASS	ROOT	DROUGHT	SHADE	FLOOD	MIN. TEMP.	WINTERKILL	SEED RATE	DEPTH
Sunflower	M	DT	E	F	P	45	28	8	.5–1
Phacelia	L	SF	G	F	P	40	20	8	.25–.75
Safflower	M	DT	E	F	P	40	24	8	.5–1
Okra	M	DT	G	F	P	60	32	8	.75–1
Buckwheat	L	SF	F	F	P	50	32	30	.5–.75
Flax	L	ST	G	G	P	40	24	50	1
Squash	M	MT	E	F	P	60	32	varies	.5–1
Beets	M	DT	G	P	P	48	26	8	.5–1.25

Forbs

CHART VALUES AND RATINGS

Biomass: biomass potential relative to other legumes. L=low, M=moderate, H=high, VH=very high

Root: root depth and type. S=shallow, M=moderate, D=deep, T=taproot, F=fibrous

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Flood: flood tolerance. P=poor, F=fair, G=good, E=excellent

Min.Temp.: minimum germination temperature in degrees F

Winterkill: temperature in degrees F at which winterkill occurs; varies with variety, snow cover, residue cover, and soil moisture.

Seed rate: recommended seeding rate in pounds per acre

Depth: recommended planting depth in inches

Making a Cover Crop Blend

When I started in the cover-crop business, the norm was to plant a single species of cover crop, the idea being that a single species would be easy to manage. Now I know that with a diversity of plants, management isn't really necessary. Diversity offers several benefits:

- It eliminates most weeds by filling all the ecological niches, and insects and diseases are seldom a problem because most insects and diseases are specific to one plant species.
- It reduces risk of crop failure; with multiple species the odds of something working is vastly increased.
- It achieves multiple goals with a single cover crop, and the sum of the cover-crop effects are often greater than the individual components would indicate.
- It provides the soil microbes with a more nutritious diet of root exudates. Some cover crops have root exudates high in sugars, some are high in protein, some are high in lipids, others in minerals. Put all of them together and you get a higher-microbial biomass, which leads to better soil. This is the biggest benefit of diversity.

But putting together a cover-crop blend can seem overwhelming if you're used to planting a single species at a time and your cropping experience is limited to a couple of crop species. To help you put together a blend, a company called Green Cover Seed (full disclosure: I work there) created an easy-to-use online tool for developing a cover-crop blend based on your goals. (See more on SmartMix.)

Fitting Cover Crops into the Operation

While cover crops can accomplish many soil and crop management goals, the goals can often be accomplished best when the cover crop is allowed to grow as many days as possible—especially if the primary goal is providing a continuous production of root exudates to feed beneficial rhizosphere organisms. To meet this goal, people are trying to find a means of establishing cover crops as soon as possible after the harvest of the previous crop, or in some situations even before the harvest of the previous crop. It is also desirable to establish cover crops as cheaply as possible and still attain the goals of the cover crop.

Following are some sample cover-crop blends for accomplishing these goals. These recipes are based on blends that I have found successful. They are not necessarily superior to others' recipes; they're just ones that I have felt worked well for me and my customers. Feel free to tweak these to fit your budget, your goals, your climate, and your conditions. I also encourage you to experiment with new cover-crop varieties and species and rates, as this is the best way to learn new tricks. Some of my best cover-crop recipes have been the result of my own or other people's mistakes.

Note: All amounts listed are on a pounds per acre basis.

PLANTED AFTER CEREAL HARVEST

This period is the primary cover-crop window. There are two planting periods after cereal harvest over much of the US. The

first occurs immediately after harvest. Species that perform best in this period are the warm-season plants. Warm-season legumes would be sunn hemp, cowpeas, mung beans, and guar. Warm-season grasses include sorghums, Sudan, sorghum-sudan hybrids, teff, crabgrass, and the millets. Warm-season broadleaves include okra, sunflower, and buckwheat. In addition, Graza radish and collards are two brassicas that have enough heat tolerance for inclusion in a mix planted in the heat of summer.

The second window is late summer, which would be a month or two after cereal harvest in the southern US, but immediately after cereal harvest in the Dakotas, Montana, and Canada. At this time (45 to 60 days prior to first frost in fall) just about all cover-crop species work—both cool season and warm season—and it is at this time that extremely diverse blends are very successful. Here are some sample summer-planted cover crop blends that I like for different situations:

- Summer nitrogen-fixing blend: 10 lb sunn hemp, 20 lb cowpea, 2 lb sunflower, 2 lb buckwheat, 1 lb okra; perhaps minor amounts of sorghum-sudan or pearl millet to add more root exudates
- Summer grazing blend for use with high-nitrogen fertility provided: 12 lb dwarf sorghum-sudan, 6 lb pearl millet, 2 lb crabgrass, 4 lb cowpea, 3 lb sunn hemp, 3 lb mung beans, 1 lb each buckwheat, okra, sunflower
- Summer grazing blend for use in low-nitrogen situations: 8 lb dwarf sorghum-sudan, 4 lb pearl millet, 10 lb cowpea, 5 lb

sunn hemp, 5 lb mung beans, 1 lb each buckwheat, okra, sunflower

- Summer-planted blend for use in stockpiled winter grazing: 10 lb BMR non-grain-producing sorghum or sorghum-sudan (photoperiod-sensitive, male sterile or late maturity), 3 lb guar, 3 lb mung beans, 3 lb buckwheat, 3 lb sunflower

LEARNING BY DOING

The Screwup Mix

This was one of those memorable moments when a mistake I made turned out well. A customer called and wanted to plant triticale for winter grazing. I talked him into trying a more complex blend, but I accidentally omitted the triticale on the order form. The customer planted the mix and later discovered the triticale was missing, and that he had planted the whole field to a double rate of all the other components.

Mad as a hornet, he called me, so we shipped him a full rate of triticale, which is what he originally wanted anyway. He really didn't believe that all this other stuff I gave him would add any value, so he planted the full rate of triticale over the top of the other mix.

He didn't speak to me for almost a year; then, out of the blue, he called. When I saw his number come up, I braced myself for a long-delayed chewing out.

Instead, he was placing another order, and he wanted *exactly* what he got the last year. I asked him to confirm: Did you really mean the Screwup Mix?

He confirmed, explaining that it turned out to be the best screwup he could remember. The number of grazing days this mix carried him through—fall, winter, and spring—still leaves me hesitant to tell anyone, for fear of setting up some epically unrealistic expectations.

Pick one of these modifications and see for yourself.

- **Planting Window 60 to 45 days prior to first fall frost,** with the goal of nitrogen fixation and compaction alleviation in a blend that will overwinter in most locations: 5 lb mung beans, 30 lb spring peas, 3 lb radish, 10 lb hairy vetch, 5 lb crimson clover, 10 lb winter barley, 20 lb oats or other spring cereal. Note: For extra spring pasture and improved alleviation of compaction, add 10 lb annual ryegrass per acre.
- **Planting Window 45 to 30 days prior to first fall frost,** with the goal of sequestering nitrogen and providing weed control in the following crop (with potential for grazing); this mix will overwinter: 60–90 lb rye or triticale, 2 lb rapeseed, 10 lb annual ryegrass
- **Planting Window 45 to 30 days prior to first fall frost,** with the goal of fixing nitrogen in both fall and spring: 10 lb hairy vetch, 20 lb spring peas or common vetch, 5 lb crimson clover, 2 lb rapeseed, 20 lb black oats or spring cereal, 10 lb winter barley

FROST-SEEDED INTO CEREALS

Frost-seeded into cereals is the historical method used to establish red clover and sweet clover. Sweet clover is the better nitrogen fixer; it is more drought tolerant, has deeper taproots, and is more tolerant of high-pH soils. Red clover is more tolerant of wet soils, more tolerant of acid soils, and more palatable to grazing animals, and it makes far superior hay (if that is desired). A seeding rate for a solid stand of either can be accomplished by broadcasting 15 pounds per acre into a cereal crop in winter, preferably with a cover of snow. If there is more than 30 pounds per acre of nitrate nitrogen in the soil when the legumes emerge, nodulation on the legumes may be poor.

PLANTED IN EARLY SPRING

These blends are designed to be planted in early spring, as a fallow replacement prior to fall-seeded wheat, or prior to a summer-planted crop. The goal here usually is to create a mulch, suppress weeds, fix nitrogen, or deal with iron deficiency in high-pH soils ahead of sorghum or soybeans. Here are a few ideas for mixtures:

- Nitrogen-fixing mix, with persistent cover and good weed suppression; works well ahead of either fall-planted wheat or summer-planted sorghum: 15 lb common vetch, 45 lb barley (on high-pH soils) or oats (on acid soils) or spring triticale (for more weed suppression), 10 lb flax

- Weed-suppressing mix ahead of soybeans or wheat: 60 lb oats, spring triticale, or spring barley; 2 lb Florida broadleaf mustard
- Spring grazing or hay mix: 60 lb spring cereal, 30 lb spring peas, 20 lb chickling vetch or 10 lb lentils, 2 lb rapeseed or collards

PLANTED AFTER HARVEST OF SUMMER CROPS IN FALL

The choices of cover crop species that work here will depend largely on when harvest occurs. If it occurs more than 60 days prior to first frost, then almost all species of cover crops can be used to benefit, depending on the purpose. If harvest occurs 30 to 60 days prior to first frost, then mostly cool-season plants should be utilized. If planted less than 30 days prior to average first frost or later, then winter-hardy plants should be favored. Here are some sample mixtures that can be used:

- Planted 45 to 60 days prior to first frost in fall; designed to winterkill and leave ground open for spring planting without need to terminate in spring: 60 lb spring cereal (oats, spring barley, spring triticale), 30 lb spring peas (or other pulse legumes), 3 lb 'Nitro' radish, 1 lb 'Purple Top' turnip, 1 lb collards; can add flax or *Phacelia* at 1 lb each for added soil benefit—this is a fairly simple but highly versatile cover crop blend that provides fall pasture, some nitrogen fixation, and some deep taproots.
- Planted 45 to 75 days prior to first frost in fall, designed to give a high level of pasture in both fall and spring; mixture is

not cheap but produces an amazing amount of forage for a long period of time; works best with a high level of nitrogen fertility to realize the yield potential: 30 lb spring cereal, 60 lb rye or triticale, 2 lb collard, 10 lb BMR corn or popcorn, 10 lb annual ryegrass. Note: If planting is delayed until 30 to 45 days prior to first frost, the BMR corn will give little value and should be omitted.

Ways to Plant Fall-Seeded Cover Crops Earlier

In many areas of the country, harvest of the main crops occurs so late in the fall that only a few cover crop species will successfully establish at that time. Getting cover-crop mixtures planted earlier can allow more diversity and more growth, leading to more cover-crop benefit, particularly if fall grazing of the cover crop is desired. Below are some ideas to allow earlier planting of cover crops.

Advancing harvest of summer crops, particularly corn, can allow much earlier planting of cover crops. I have often said the biggest waste of sunlight on the planet, with the exception of totally bare soil, is the month between the time when corn "black layers" (when the grain becomes mature) and when the grain is dry enough to harvest and safely store without molding. Options to get the crop out earlier include:

- Harvest at high moisture and ensile it (which requires that the crop be fed to livestock rather than sold as cash grain).

- Harvest ear corn or earlage and put into an oxygen-limited structure.
- Harvest at higher moisture, and dry the grain.
- Use shorter-season varieties.

Aerial seeding covers into maturing summer row crops. This works well when you expect rain or have overhead irrigation. The best time to put covers into corn is when the lower leaves have dried up to the ear leaf; otherwise, sunlight is limiting. I have also found crickets can wreak havoc on newly emerged cover-crop seedlings. (Note: You can combat crickets with baits designed for them.) The best time for aerial seeding into soybeans is when the leaves have turned yellow and are getting ready to drop.

Seeding into corn at "lay-by." Lay-by refers to the last pass of the season with a cultivator. This was once a common practice in the Corn Belt. Do you ever wonder why we have fall decorations of pumpkins with shocks of corn? It is because pumpkins and pole beans were seeded in between rows of corn with a planter unit behind a cultivator shovel. The pole beans and pumpkins were seeded to add additional livestock feed (or human food) for postharvest grazing of the crop residue.

Some folks are getting a bit earlier start nowadays, with the interseeded crop being planted as early as the six-leaf stage of the corn. Research has found that any crop that emerges after the six-leaf stage will not affect corn yields, but this can capture some of that otherwise wasted sunlight that falls between corn plants early in the season and convert it into

something useful. The crop also has a bit more time to get itself established before the corn canopies over it.

Interseeding by machine prior to harvest. The agriculture machinery manufacturer Hagie now makes a tall, narrow-tired spray rig that can be fitted with a modified spray boom. The boom has been altered to deliver not chemicals but seeds (through tubes with air jets) and drop them in between the rows at any stage of the corn crop growth cycle. Compared to aerial seeding, less seed gets caught in the leaf axils, and less of it travels off-site.

Having pulled too much rye out of my neighbor's wheat fields after a careless pilot spread seed a little too far past my boundary, I recognize that as a significant advantage. Weight of seed per acre is also less of an issue than with aerial seeding, in which high seeding rates per acre become increasingly costly.

Modified seeder/mulcher. A couple of years ago I became acquainted with two men who were buying secondhand detasseler machines that had been used in seed corn production. They were modifying the machines to walk through corn fields just after black layer and broadcast seed out in front of the machine, then cut off the tops of the corn plants right above the ear. This system has many advantages:

- Like the Hagie spray rig described above, the seeder/mulcher can walk in between the corn rows when the crop is mature.

- Cutting the tops off the corn after the seed is dropped means the tops drop on top of the seed and become a mulch to aid germination.
- Cutting the tops off dramatically increases the amount of sunlight available to newly emerged seedlings.
- After removing the tops, the ears are exposed to more sun and more wind, so the crop dries faster, and harvest can occur earlier and thereby expose the cover crop to full sunlight sooner.
- Since the crop is made shorter, the wind applies less torque on it, so the crop should stand better until harvest.

Companion cropping. The concept of mixing different cover-crop species together has been so successful that farmers have begun to explore planting crops to be harvested for grain or seed in mixtures of multiple species. This can offer several benefits:

- The diversity of crops reduces risk from any one disease or insect becoming a problem.
- A mycorrhizal host can be blended with a non-mycorrhizal host crop to maintain populations of mycorrhizal fungi (rather than lose the population after growing a nonhost, such as canola, for a season).
- A legume can help provide some nitrogen to a nonlegume companion crop.
- The layering of roots and leaf canopies can allow for "overyielding," where the total yield of the components is

greater than the weighted average of the components grown separately.

- The diversity of root exudates contributes to higher microbial populations.
- Price risk for any one crop is reduced.

One example of companion cropping is growing oats and spring peas together; another is growing winter peas and winter canola together. The seed can be separated after harvest, if pure seed is desired, or they can be planted together for another crop. Or if both components have value as feed, then they can simply be fed together. I think a blend of spring triticale, spring peas, and flax would make a really nice feed for poultry, and all could be planted and harvested at the same time.

Relay-seeding into small grains. At one time it was common practice in the Corn Belt to broadcast seed clover into a growing small-grain crop. The clover would be only a few inches tall when the small grain was harvested but would take off after the grain canopy was removed, giving it full sunlight. Herbicide use on small grains, especially long residual sulfonylurea herbicides, proved injurious to clover seedlings, and high rates of nitrogen applied to the small grain to maximize grain yield inhibited nodulation of the clover. This practice still works, particularly in organic production where herbicides and synthetic nitrogen fertilizer are not used.

If You've Got the Time . . .

I thought the seeder/mulcher was one of the more brilliant ideas I had ever heard. Then I told an Amish guy in Missouri about it. He said, "Well, that is impressive, but I can do better than that."

I asked him how. He explained that he would broadcast the seed by hand with a whirligig hand spreader between the rows of corn, one acre's worth a day. He would fence off that acre from the rest with electrified woven wire netting, then turn sheep in to eat the lower corn leaves and trample the seed into the ground. (He selects corn hybrids with high ear placement, above the reach of the sheep, so the corn grain is left alone.) Next he runs a sickle bar across the field, just above the ears of corn, to feed the sheep the tops of the plants.

When he is finished with the acre, the corn ear and bare stalk remain protruding above a cover crop that has been pressed into the ground with sheep hooves and then mulched and fertilized with sheep manure. He repeats the same process across the field.

Wow. That certainly was even more brilliant than the modified detasseler. But it also sounded like an insane amount of work, and I told him so. He said, "Well, I only got 12 acres, so it ain't that much work. And besides, I'm

Amish, so I ain't got a TV, and I need something to do to keep from getting bored."

CHAPTER 10 SUMMARY

- Cover crops can:
  - reduce soil erosion
  - improve infiltration of rainfall
  - reduce evaporation of soil moisture
  - improve soil organic matter
  - increase populations of beneficial soil organisms
  - improve soil aggregation and aeration
  - provide livestock grazing
  - fix nitrogen and improve availability of other soil minerals
  - reduce soil compaction
  - increase depth of the root zone
  - control weeds
  - increase wildlife
  - reduce flooding, and
  - improve timeliness of cropping activities.
- Many species of plants can be used as cover crops, including many species of grasses, legumes, and forbs. Common cover crops include cereal rye, annual ryegrass, oats, radishes,

sunn hemp, and hairy vetch. Each plant has advantages and situations in which it may be beneficial.

- As cover cropping becomes more popular and its advantages realized, more and more innovative methods of establishing cover crops are being created, especially to establish cover crops prior to the harvest of the preceding crop.
- The bottom line: Plants fix soil. The trick is finding the right plants for the situation.

11

Pasture and Rangeland Management

Author's note: I have written an entire book on the subject of grazing management, entitled *Managing Pasture*. This chapter is a highly abbreviated version of that book. If it leaves you hungry for more, I encourage you to read the book.

Let the Sun Shine In

The best and fastest way to build soil is to have an uninterrupted flow of solar energy into the soil through photosynthesis. With annual crops, even with cover cropping, there are unavoidable periods during crop establishment in which there is minimal photosynthesis. The best route to soil improvement, therefore, is to have land in a complex blend of perennial vegetation with overlapping growing seasons. This will fully utilize sunlight whenever moisture and temperature conditions allow.

As of right now there are no perennial grain crops (though that may be only a temporary situation; see Chapter 13), so utilizing perennial vegetation to produce food involves either tree crops or grazing animals, or some combination thereof. Of the world's land mass:

- Rangelands and pastures make up about 27 percent.
- Cropland is about 11 percent.
- The remainder is split fairly evenly between forest (mostly the cold forests called taiga in northern Canada and Russia)

and desert (especially on Antarctica, which is technically a desert since precipitation occurs so rarely there).

Since pastures and rangelands occupy a much larger percentage of the world's land area than cropland, they have far more potential impact on the global environment than croplands do. They could store more carbon in the soil than any other system, for example, due to their large footprint on the earth and the fact that rangelands are already populated by the perfect plants with which to do this: perennial grasses.

Unfortunately, most rangelands are in a seriously degraded condition and are far short of realizing their potential.

Fortunately, on the other hand, degraded rangeland can be rather easy to repair. It just takes proper grazing management. But the emphasis here is on the word "proper."

The Economics of Photosynthesis

Photosynthesis requires that sunlight fall on an actively growing leaf. Improper grazing management—either undergrazing or overgrazing—often results in sunlight not being captured by active leaves. The science of grazing management currently focuses on maintaining pasture plants at optimal photosynthetic capacity for as much of the year as possible.

For centuries, livestock were basically free-ranging under the guidance of a herder, who kept them from straying too far. When the forage was grazed off, the herder moved the stock to greener pastures. Under extensive conditions, with unlimited

free pasture and low populations, this worked quite well; however, as populations of both humans and domestic livestock increased (and both became confined by subjective property boundaries), overgrazing became common.

Today, virtually all pasture land is enclosed, and much of it comes with a price tag in the form of rent or a mortgage payment. Because this makes it desirable to maximize economic return off that land, the typical approach is to cram as many animals as possible into the area, and quite often a few more than that. Every stock owner knows that overgrazing is bad for the grass, and most realize when they are overgrazing, but they feel they have to overgraze in order to maximize their income.

This is perhaps the biggest fallacy in agriculture—the notion that income from pasture is maximized by overgrazing. I can't even begin to count the number of times I have visited a ranch and the operator apologizes for the overgrazed conditions of their pastures. They then explain that they are forced to do this because the rent or the mortgage is so high that they have to get all the good they can out of it. They can't afford to "waste grass."

Pasture and Profit

The reality is that money comes from meat, meat comes from herbage, and herbage comes from photosynthesis. Pastures grazed so low that sunlight hits bare soil perform little photosynthesis, thus producing little herbage, little meat, and little money. By contrast, a well-designed grazing system

allows the forage plants to maintain enough leaf area to continue photosynthesis at an optimal rate and simultaneously provide optimal economic animal performance. Grass that never grows because it is overgrazed is "wasted" just as surely as grass that is grown and not grazed.

The Importance of a Proper Stocking Rate

The data opposite should dispel the notion that greedy ranchers overgraze in order to make profit. The most profitable stocking rate was also the one that best maintained the rangeland. Research similar to this has been conducted all over the world with almost identical results.

To become a good pasture manager, there is one overriding principle you must follow: Maintain optimal animal performance and optimal pasture performance at the same time. The single most important decision to make in managing pasture is to determine a proper stocking rate. If a stocking rate is too low, it's essentially leaving money on the table because there are fewer animals to sell. If the stocking rate gets too high, animals perform poorly due to too much competition for forage, and the pasture suffers.

Determining an exact, proper stocking rate prior to the growing season is an impossible task, just like predicting the exact score of a football game before the season starts. There is too much that can happen later on; it can rain, or not; it can be

too cold or too hot or too something else. In reality, you start with an educated guess, then adjust on the fly as the season goes on.

HOW STOCKING RATE AFFECTS CATTLE GAIN AND PROFIT

This data, comparing the profitability of different stocking rates, is from the Kansas State University Kansas Agricultural Experiment Station at Hays, KS.

STOCKING RATE	$/HEAD	$/ACRE
Light (5.0 acres per head)	$26.04	$5.21
Moderate (3.4 acres per head)	$16.91	$4.97
Heavy (2.0 acres per head)	-$7.31	-$3.65

This study was updated with current prices by Keith Harmoney of Kansas State for the period 2006 to 2010. I thought the original data interesting because the light stocking rate was the most profitable, and the heavy actually lost money. The Harmoney figures probably reflect more current conditions, but I found the original illustrates my point that proper grazing is more profitable than abusive grazing.

STOCKING RATE	$/HEAD	$/ACRE

HOW STOCKING RATE AFFECTS CATTLE GAIN AND PROFIT

Light (5.0 acres per head)	$91.70	$18.34
Moderate (3.4 acres per head)	$75.64	$21.63
Heavy (2.0 acres per head)	$24.95	$12.48

HOW GRASS DEFOLIATION AFFECTS ROOT GROWTH

	% NONGROWING ROOTS		
% LEAF REMOVAL	RHODES GRASS	SMOOTH BROMEGRASS	KENTUCKY BLUEGRASS
10	0	0	0
20	0	0	0
30	0	0	0
40	0	0	0

SOURCE: F. J. Crider, "Root growth stoppage resulting from defoliation of grass," *USDA Technical Bulletin 1102*, (1955).

HOW GRASS DEFOLIATION AFFECTS ROOT GROWTH

50	2	13	38
60	50	36	54
70	78	76	77
80	100	81	91
90	100	100	100

SOURCE: F. J. Crider, "Root growth stoppage resulting from defoliation of grass," *USDA Technical Bulletin 1102*, (1955).

Determining a Stocking Rate

So how do you determine the proper stocking rate? Grasses grow differently from broadleaf plants, but since most pastures are primarily grasses, if management is conducted to ensure good grass vigor, the rest of the plants in the stand will ordinarily be in good vigor as well. The proper stocking rate for grasses will remove enough herbage at one grazing so there is enough residual leaf area left that photosynthesis continues uninterrupted. If too much herbage is taken at any one grazing event, then the production of energy in the plant ceases and both root growth and leaf production is stopped. The data on the facing page illustrate how taking just a little too much leaf

area at one time can result in a drastic reduction in root growth.

Since most of the soil-creation benefit of a perennial grass is derived from the root system and root exudates, it is absolutely essential that grazing pressure be maintained at an optimal level if the goal is better soil.

Stocking rate is a function of number of animals, the intake of the animals (bigger animals eat more), and the time they are on the pasture. One way to determine a beginning stocking rate is simply to go with the prevailing stocking rate of the area. Take note of pastures in the area that simply “look good” compared to ones that are obviously poorly managed. You don’t need to be a PhD in rangeland ecology to know what is overgrazed. Ask the operators of the good pastures what their stocking rate is. This approach can get you close to a proper rate, as long as your pasture situation is similar (pasture species composition, soil texture, soil depth, soil fertility, topography, etc.).

A more scientific approach is to go to the USDA Natural Resources Conservation Service office (there is one in nearly every county in the US) and ask for a stocking rate determination. They have a computer-based program that calculates stocking rates based on soil types, pasture species, and pasture condition in a given area. This can give you a very accurate starting point. With innovative management, it is possible to greatly surpass these rates, but it is essential not to increase stocking rates until an increase in pasture growth is apparent.

Meeting Animal Needs Year-Round

Maintaining animal performance requires an understanding of how animal needs change throughout the year. Lactating or growing animals require much higher quality and quantity of forage than nonlactating mature adults. This difference is key to profitable pasture management. For example, the table below illustrates how the needs of a beef cow change throughout her production cycle.

To meet needs of both plant and animal, it is important to understand exactly how grass grows. Grasses have a typical life cycle of three parts.

HOW A BEEF COW'S NEEDS CHANGE DURING THE PRODUCTION CYCLE

STAGE OF PRODUCTION	LBS OF CRUDE PROTEIN NEEDED PER DAY
Nonlactating	1.5
60-day period prior to calving	1.8
Lactating	2.3

VEGETATIVE STAGE

During the vegetative stage, leaves are being produced rapidly, there is little stem material, and the growing points are

belowground. Since less mature forage is more nutritious than mature forage, and leaves are more nutritious than stems, nutritional quality for grazing livestock is very high. The grass is also fairly tolerant of grazing at this stage because animals remove few growing points, and regrowth is very rapid, provided sufficient leaf area is left after a grazing event to maintain photosynthesis.

REPRODUCTIVE STAGE

The reproductive stage begins when the seedheads start to elongate and become visible. The growing points elevate aboveground and become vulnerable to grazing, and leaf production slows. Reproductive forage is of much lower quality than vegetative and is much more intolerant of close grazing at this stage.

DORMANT STAGE

Dormant forage is not growing at all. In areas with cold winters, or dominated by warm-season grasses, the dormant period is winter. In tropical areas with a dry period, it is the dry season. In Mediterranean climates (such as that of California), it is the very dry summer. Dormant forage has very low nutritional value, although some species are more valuable than others (notably, tall fescue). Ordinarily, however, it can be completely grazed without harm to the grass. It is usually desirable to maintain a minimal amount of surface residue to provide soil protection and maintain water infiltration, but it is also desirable to remove much of the now-dead residue so that sunlight can reach new growth.

As explained in the carbon:nitrogen ratio discussion in Chapter 6, protein content of most dormant warm-season grasses is so low that it is often considered useless as livestock pasture, because the rumen microbes have insufficient protein to reproduce. With a low amount of protein supplement, however, dormant forage can be a very useful pasture source for animals with low nutritional need, such as nonlactating, mature cows.

Defoliation during the reproductive period is most detrimental to grasses. Grasses can be grazed during their reproductive period, but that might require a taller residual height afterward than after vegetative grazing.

HOW GRAZING AFFECTS GRASS AT DIFFERENT STAGES

STAGE	RELATIVE NUTRITIONAL VALUE	RELATIVE HARM DONE BY INTENSE GRAZING
Vegetative	High	Low
Reproductive	Medium	High
Dormant	Low	None

How It Adds Up

A couple of vital principles:

- If dormant forage has no value, there is no apparent financial incentive to maintain at least the minimum amount of standing dormant forage required for good grass vigor.
- If dormant forage has value equivalent to green forage, then ensuring an adequate amount of it at the onset of dormancy becomes financially important, even in the short term.
- Finding ways that animals can economically graze forage during the dormant season thus incentivizes leaving an adequate stubble during the growing season to maintain optimum photosynthesis and plant vigor and productivity.

Ultra-High Density Grazing

DANIE SLABBERT, Reitz, South Africa

Nonselective ultra-high-density grazing (NSUHDG) involves multiple paddock shifts per day, with very high livestock densities to encourage animals to eat or trample each and every plant in the paddock. This has proven to be quite useful in locations with extreme variability in the palatability of grasses.

In the typical set-stocked, continuously grazed management system, the animals eat palatable species to bare ground and ignore unpalatable species. NSUHDG ensures that all plants are eaten equally, palatable and unpalatable alike, which levels the playing field and allows the palatable species a fighting chance. Then, to restore plant vigor, a long rest period—sometimes more than a year— follows the highly intensive grazing period.

I visited one such system at Danie Slabbert's farm near Reitz, South Africa. His mixed herd of cattle and sheep are grazed together on the *veld* (natural grassland), in large numbers at high animal density, and moved six to ten times per day. When the animals exit a paddock, not a single plant is left unscathed. Even thistles—the literal thorns in the sides of many pasture managers—are consumed, and after a while they and the other weeds just disappear.

This severe grazing episode harms the grasses, but it harms the normally ungrazed *Eragrostis* grass plants just as much as it harms the normally heavily grazed desirable grasses—thus "leveling the playing field" between desirable grasses and unpalatable grasses. It is followed by a very long recovery period of 18 months. That means that not only do the plants receive a full growing season of rest before the next grazing, but, since there is a 6-month growing season and a 6-month dormant period, that every other grazing episode occurs during the dormant season.

As a result, a plant gets grazed during the growing season only once in 3 years, but grass does not get wasted. The nearly 100-percent removal rate during the infrequent grazing periods makes sure that all vegetation gets run through a rumen at some point.

It Couldn't Work . . .

I can tick off several reasons why I believed this system would not work:

1. The severe grazing will drastically stunt the grass plants, which cannot tolerate such extreme defoliation, and root growth will cease.
2. Forcing animals to consume the entire plant, including lower stems, will result in very poor animal performance.

3. At times the animals will consume very mature plant growth of low nutritional value, without access to highly nutritious regrowth, which will also result in lower animal performance.

. . . and Yet It Did

Once I set foot onto Danie's farm, however, and saw the results, I was blown away. His neighbor's pasture consisted of clumps of unpalatable *Eragrostis* species with, in between, large areas of grasses grazed down to less than an inch (2.5 cm) in height. Across the dirt road, after three years of NSUHDG, Danie's paddocks were very tall and so dense I felt as if I were walking on the straw mulch in a garden.

The species composition was largely the highly desirable red grass (or rooi gras) and *Paspalum* species with very low amounts of *Eragrostis*. In addition, Danie is now seeing the return of long-absent clovers and other native legumes. There is no question that this form of grazing has elevated his veld to a state of incredible natural productivity.

HOW DID THE ANIMALS RESPOND?

But what about animal productivity? It isn't great—but it isn't awful, either. Cattle conception rates are lower than he would like, but he says this is because he began with genetics that didn't fit the situation. For an animal to thrive

in such a system, it needs two key traits: a small frame, and thus low maintenance requirements; and a very high rumen capacity, so it can compensate for low-quality forage with higher levels of intake.

Danie is selecting for animals that fit just such a system, retaining only heifers that calve at both 2 and 3 years of age. While this is common in the US, with our high levels of supplemental feeding, in the low-nutrition "sour veld" found in Danie's area, it is common for heifers to have their first calf at 30 to 36 months of age.

In addition to genetic selection, the multiple moves per day stimulate intake. Just as people on Thanksgiving will sample every new dish when it is brought out, no matter how full they already are, cattle will get up and eat each and every time a new paddock is opened up. The animals are also often given a probiotic supplement or a urea-containing mineral to aid digestion of low-quality forage.

Finally, the electric fence wires are set high so that Danie's sheep can crawl under and reach the best parts of the next paddock, and this selectivity results in good performance. He says that the sheep are the real moneymakers, and the cattle are in the system to improve the veld.

But here is the real kicker. Danie can carry *five* times the livestock units per hectare of his neighbors. Even if his conception rates were to drop to a very low 50 percent, he would still produce 2.5 times the number of calves of his neighbors—even if they have 100 percent conception (and that never happens, since around 80 percent is normal for most herds in Africa).

The heifers and bull calves that he retains will eventually be the basis for a highly desirable line of breeding stock that can thrive on low-quality forage. In addition, his veld improves each and every year.

After seeing the results first hand, I have no doubt that Danie will achieve these goals, and I am excited to see the changes over time.

Maintaining Healthy Pasture

Maintaining pasture in a healthy condition involves the following major management principles:

- Maintain adequate residual leaf area after grazing.
- Maintain adequate recovery period after grazing, before the plants are grazed again.
- Maintain uniformity of grazing pressure across the landscape.

Continuous vs. Rotational Grazing

There are two main forms of grazing management: continuous and rotational. Continuous grazing is quite simple: The animals are left in the same pasture until the end of the grazing period, which all too often is when all the feed is completely consumed. Rotational grazing involves subdividing

the pasture into several smaller units and grazing only one at a time, then rotating the animals on a periodic basis to the other units.

Continuous grazing, if done at a low stocking rate, usually has the best animal performance because animals are free to select which plants and plant parts are most nutritious. However, because animals tend to repeatedly graze the regrowth of their preferred plants, those plants tend to lose vigor and become unproductive, while unpalatable plants tend to become increasingly more abundant. This can be managed with very low stocking rates, but with the typical temptation to graze more than is really advisable (or profitable), continuous grazing often results in pasture degradation and eventual poor economic performance.

Rotational grazing does not guarantee better grazing results. If mismanaged, it may actually exacerbate pasture deterioration due to overgrazing and may dramatically reduce animal performance. In my experience, rotational grazing all too often becomes rotational *overgrazing* because the temptation is to leave animals on an area until they have consumed every last bite of the herbage available, and later the animals are returned before adequate recovery has been achieved. This is a very common mistake.

That said, rotational grazing makes it possible to combine a higher stocking rate with good animal performance, and without pasture degradation, but it requires management and observation. To paraphrase Allan Nation, late editor of the *Stockman Grass Farmer* magazine, continuous grazing is like driving a grain combine without a steering wheel or brakes.

Rotational grazing allows more control but is no better than the person steering the system. In the hands of a knowledgeable grazing manager, however, rotational grazing can be a phenomenal tool.

A properly managed rotational grazing scheme makes it easy to control the important factors of pasture management mentioned above (adequate residual leaf area and recovery period and uniformity of grazing). Maintaining pastures at a very high level has become much easier over the past few decades with the development of movable, temporary electric fencing stems and portable watering systems.

In the hands of a knowledgeable grazing manager, . . . rotational grazing can be a phenomenal tool.

THE GRASS GROWTH CURVE: A GUIDE TO ROTATIONAL GRAZING

After grass is grazed once during a season, it will begin to regrow and reestablish its canopy. How fast the canopy regenerates after the grazing event depends on several factors:

- the severity of the prior grazing episode—how much leaf area remains after grazing

- the vigor of the plant prior to grazing—from a combination of growing conditions and grazing management prior to the previous grazing event
- the growing conditions: moisture, temperature, sunlight, soil fertility, and physical condition

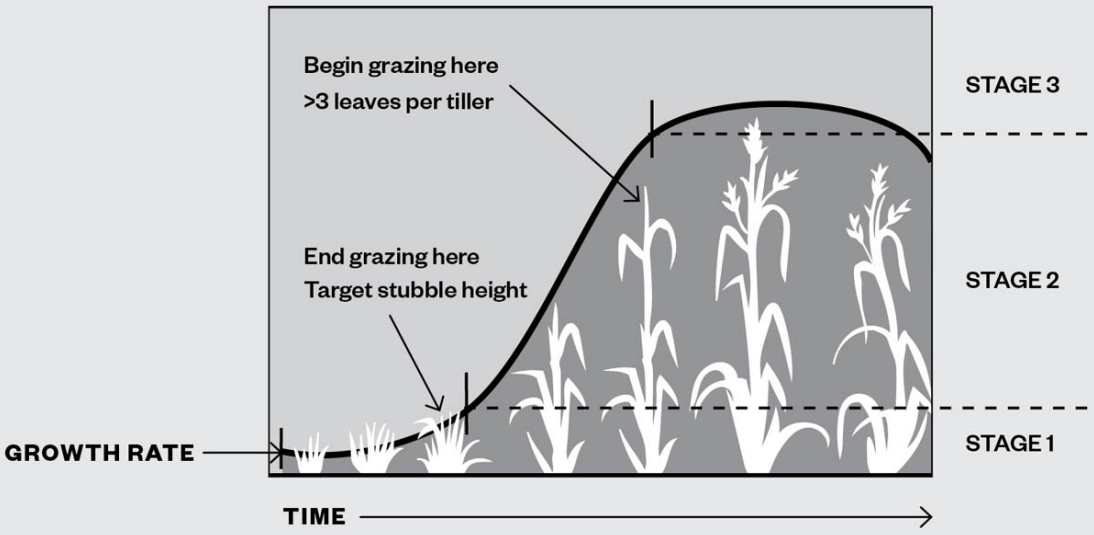
The grass growth curve is a tool to aid management of rotational grazing. The curve includes three parts, or stages:

Stage 1: This is growth when there is no leaf area to capture sunlight, such as the initial growth in spring, and the plant has to establish a canopy from stored reserves so it can begin photosynthesizing. If growing plants in later stages are grazed too severely, and too much leaf area is removed, then the plants can be set back into Stage 1 again.

Stage 2: This occurs after the leaf area has reached a critical mass and begins to generate a surplus of carbohydrates with which the plant can generate new leaves at a very rapid rate. Nutritional quality of the grass to grazing animals is also very good. The signal for the beginning of Stage 2 differs from plant to plant; once the season begins, it is usually signified by a certain height of grass leaf blades.

Stage 3: This is when the grass becomes mature, and growth slows down. Lower leaves are now often shaded

by the upper leaves and do not contribute to the plant. Nutritional value of the plants is now relatively low as well. Biomass is high, but growth rate is low. Over time, standing biomass may actually decrease, as lower leaves senesce. The beginning of Stage 3 for most grass plants is when tillers have more than three fully formed leaves, although some (such as orchardgrass and perennial ryegrass) typically form only three.



Pastures Replace Feedlots

CACTUS FEEDERS, Texas Panhandle

Not many environmentalists look favorably on confined animal feeding operations (CAFOs), for a number of reasons. Some object to the confinement itself, believing it is inhumane and unhealthy to keep animals in such crowded conditions. Others object to the diet, feeling either that grain is not a natural part of a ruminant's diet or that livestock should not eat food that humans could otherwise eat. Still others oppose the eating of meat, period. Many will cite all these factors for their opposition to CAFOs.

A Little History

Confined animal feeding has long been a part of the agricultural landscape, but until the last half-century it was practiced on a very small scale on family farms. In the period following World War II, however, cheap fertilizer, cheap fossil fuel, cheap machinery, and cheap concrete combined to make feed grains, like corn, cheap as well—and abundant. Additionally, the discovery of underground aquifers and the invention of center-pivot irrigation made the production of corn possible in otherwise arid areas.

This was key to the development of beef feedlots in the western Great Plains region of the US. Formerly, beef

cattle were fattened in the Corn Belt, where corn was readily available and locally cheap. But the Corn Belt's characteristic mud and humidity (both of which dramatically reduce animal performance), as well as the high cost of land there, made the arid High Plains a more economical choice for cattle finishing.

Now, however, traditional cattle-feeding operations in the area are experiencing some troubling times. The diminishing water supply in the Ogallala Aquifer, the current poor economics of cattle feeding, environmental restrictions, and animal welfare pressures are all converging to make the confined feeding of cattle much less profitable than it formerly was.

A New Direction

But one High Plains cattle-feeding operation is experimenting, by radically altering the way they fatten cattle, with impressive results in water usage, environmental impact, animal welfare, and economics. Cactus Feeders, with 11 locations centered in the Texas Panhandle, has been expanding a grazing program on fields that formerly grew corn, irrigated by center pivots. Some of these pivots draw from a declining water supply and could no longer keep up with the water demands of corn in the area.

The grazing project was originally designed to produce grass-finished beef on a mass scale, but the buyer backed out. Cactus had to market the beef into the commodity beef

market, and the pasture program seemed over and done. But a curious thing happened. Upon examining the financials of the grazing operation, Cactus discovered that they made *more* money on the cattle finished on pasture than they were making on cattle finished on grain, even without the promised premium they were not able to collect. (See Figure 9.2.)

This was to everyone's surprise, as it is assumed that the most economical way to finish cattle is to feed them corn in confinement, and that pasture does not have the energy density to economically fatten animals. Even more surprising, the difference in costs was not small; it was actually very strongly in favor of the pastured cattle. So even though the grass-finished program went away, pasturing animals on high-quality irrigated pastures has become a long-term feature at Cactus Feeders.

Seasonal Sequence of Pastures

The key to maintaining high animal gains is to provide a sequence of different pasture types that can deliver high-quality pasture for a long period of time. To fatten properly, a beef animal must gain over 2 pounds (0.9 kg) or so each and every day of the finishing period, which can range from 4 months to as long as 10 (if the animals are placed as lightweight calves). Very few single pasture species can sustain quality over this length of time, so a seasonal sequence of annual pastures was devised to

allow the animals to be moved to finishing-quality pasture for 10 months or more of the year.

In the fall and spring, animals are pastured on winter annual grasses and cereals like black oats, winter triticale, annual ryegrass, and winter forage wheat. During the spring, as a pasture of winter annual grasses is nearing the end of its life cycle, it is killed and planted to a summer grazing mixture of dwarf brown midrib sorghum-sudan, pearl millet, crabgrass, cowpeas, mung beans, sunn hemp, okra, sunflowers, and buckwheat. This diversity of plant species provides a most nutritious “salad bar” that sustains animal gains even during the Texas heat in July and August.

In addition to the annual pastures, Cactus is planting some perennial pastures that will be spliced into the grazing rotation, to supply grazing during the times when annual pastures are getting established. The deep-rooted perennial grasses and legumes will be even more water efficient than the annual pastures, and they will not need the yearly planting, spraying, and fertilization that the current annual pastures require, resulting in even more economical gains. Some of the perennial pastures will provide quality grazing during midwinter, others in late spring and early fall, in the gaps when annual pastures are not productive.

A Multitude of Benefits

One of the more impressive aspects of this program has been the very rapid soil improvement seen on these pastures; in the initial year of the project, one field (planted to a summer grazing mixture and inoculated with mycorrhizal fungi) climbed from 1.6 percent organic matter to 2.2 percent organic matter in one growing season! (See Figure 8.2.) That is some serious carbon sequestration in an area in which accumulating soil carbon is quite difficult.

Other ancillary benefits are emerging as well: There is less dust and crowding, so respiratory diseases are greatly reduced; and manure disposal costs are eliminated, since manure is simply left in place to benefit the next crop in rotation.

TIME-TESTED TECHNIQUES

Over the years, the system has morphed from a limited-scale grass-finishing operation to a larger-scale one in which the animals are grazed most of their life and placed in the lot only for the final stage prior to harvest. (The closer animals get to harvest, the more energy dense the diet needs to be to maintain gains, and gains on forage alone become less and less economical.)

Cactus Feeders has shown that the environmental footprint of cattle feedlots can be greatly reduced with the incorporation of a pasture program. The net result has been:

- a reduction in water use (the irrigated pastures use about half the water of corn)
- a reduction in fuel use (most of the fuel goes to the center-pivot irrigation systems)
- a reduction in fertilizer, herbicide, and insecticide use.

While all these factors provide environmental benefits, they also help improve the profitability of the operation.

Neighbors, the feedlot industry across the country, and the state of Texas have all taken notice. Cactus Feeders earned one of the prestigious "Texan by Nature" awards in 2019. According to Tyler Dinkel, grazing manager at Cactus Feeders, the program will definitely expand in the future as they work out the kinks inherent in any new enterprise. Logistical issues (such as providing sufficient drinking water for the sometimes one-thousand-plus animals on one field at a time), adequate fencing, and matching the available forage with animal intake are being slowly resolved, and each year the program grows stronger.

GOALS OF ROTATIONAL GRAZING

The usual goal with rotational grazing is to maximize animal production per unit land area. This is accomplished by maximizing the photosynthetic rate and by optimizing the conversion of plant material into animal product. Photosynthesis is maximized by maintaining a full plant

canopy with adequate leaf area—but not excessive coverage so that lower leaves cannot contribute. Converting plant material into animal material means plants must be consumed before they get too lignified and digestibility drops.

These goals are achieved by grazing just before Stage 3 occurs and pulling animals off before the grass is converted into Stage 1. As noted, the time it takes for a plant to reach Stage 3 after grazing depends on a number of factors and involves several considerations, described below.

How Hard Should a Paddock Be Grazed?

What is adequate residual? In other words, how much *leaf* should you *leave*?

Residual is the amount of leaf area left after a grazing event. How much leaf area to leave depends on how much is needed to generate regrowth after a grazing event. Some plants, like alfalfa, can store a large amount of carbohydrates in the roots—if the plants are allowed to grow long enough to bloom—and they can use that energy for regrowth even if all leaves are removed at grazing or haying. But most grass plants store relatively little energy in the roots and require leaving about a 4-inch-tall (typically) stubble after grazing. Some grasses, like eastern gamagrass, store energy for regrowth in the bases of the leaves and are intolerant of grazing below an 8-inch stubble height.

The proper residual also depends on where the growing points are located on the plant. Some plants (such as smooth bromegrass, Indian grass, switchgrass, and timothy) have growing points located high aboveground and are rather

intolerant of close grazing. Others, like Kentucky bluegrass, white clover, tall fescue, and buffalograss, have growing points just above the soil surface and can handle close grazing, though even these do best with an adequate residual leaf area remaining after a grazing event.

When Should Grazing Occur?

The time of year and growing conditions also have an effect. The slower the growth rate, the more leaf area it takes to generate enough energy for regrowth and vigor. This creates a problem, as animals will want to take their fill and will graze a higher percentage of the forage as growth rates decline unless stocking rates are reduced. Animals eat the same whether plants are growing normally or not, but the plants actually require more residual leaf area in these conditions than normal. Ordinarily, late summer and early fall are the periods when most overgrazing occurs, as the growth rate on all cool-season grasses and most warm-season grasses slows down considerably.

Photosynthesis is maximized by maintaining a full plant canopy with adequate leaf area—but not excessive coverage so that lower leaves cannot contribute.

If you ask a number of people, "What is the cause of overgrazing?" they will almost certainly tell you that the pasture has too many animals on it. They would be incorrect. . . . The correct answer is that overgrazing is

caused by too many animals in one place for too long and too often.

And How Much Should Animals Be Allowed to Eat?

In general, the old rancher's rule of thumb of "taking half and leaving half" has considerable validity as a grazing guideline. Basically, it means that in order to maintain long-term productivity, no more than half of the current year's growth should be removed during the growing season. As can be seen in the data, perhaps the old saying should actually be: "Take 40 percent, and leave 60 percent."

A common problem of the "take half, leave half" approach is that it can be difficult to see how much grass has disappeared, compared to the residual left. One way of doing this is to construct grazing exclosures, or small areas that are left ungrazed, to act as a monitor of grazing pressure. These are easily constructed from a welded wire cattle panel folded into a circle and anchored by two steel T-posts.

An easier and perhaps more accurate approach is to simply remove animals from a paddock when target heights of residual have been reached, rather than trying to guess the percentage of removal. For the vast majority of pasture grasses in the US, that target height is usually 4 inches—no less. A huge temptation among graziers is to "get one more day's worth" of grazing out of a paddock. This should be avoided at all costs. The extra stress of grazing down to a 2-inch stubble height delays regrowth considerably and reduces overall productivity greatly, as illustrated by the data.

Another complicating factor of how much residual to leave is determining the goal of the grazing management. I have noted that the usual goal is maximizing animal product per unit of land area. But what if the goal is different, such as rangeland improvement or wildlife management? Then these rules change. For an example, see the sidebar on nonselective, ultra-high-density grazing.

How Long Should Animals Remain in One Paddock?

Ordinarily, the less time animals remain in one place, the more efficient the grazing period becomes, the more uniform the grazing pressure, and the more weeds and unpalatable plants are consumed. The primary goal of limiting time in any one area is to reduce grazing of new regrowth and to maintain uniformity of nutritional quality from day to day. Keeping grazing periods to less than three days per paddock is desirable. I have seen impressive results from paddock moves as often as six times a day.

What Is an Adequate Recovery Period?

After a plant is grazed down it requires a period of rest to regenerate its roots and leaves before it is grazed down again. How long it takes to regenerate a plant depends on how fast the plant is photosynthesizing. Plants grazed too hard, with little remaining leaf area, will photosynthesize much slower than plants with adequate leaf area. In the moderate temperatures and long days of bright sunlight in May or June, with plentiful moisture, it may take as few as 20 days to fully regenerate. On the end of the spectrum, in the shorter days of fall, with

sporadic or scarce moisture, it may take 60 days or more to achieve the same degree of recovery.

This explains why rotational grazing schemes based on fixed periods of rest are seldom successful. A successful rotational grazing system absolutely *must* be based on observation, not on a calendar. The main problem is that the growth rate of a pasture *never* matches the forage intake rate of the pasturing animals in the real world. Therefore, it is essential that there is flexibility in a grazing system to allow for this mismatch and ensure adequate quality and quantity of forage for the animals—and at the same time to ensure that as much forage as possible is converted to economic use without grazing below the required residual stubble height.

What Constitutes Adequate Recovery?

In most legume plants, adequate recovery is often signaled by blooming. In grasses, there is no such easily visible sign. Many grass managers will count leaves on a tiller. A tiller that has four fully formed leaves is considered fully recovered, although with some common species such as ryegrass and orchardgrass, three leaves per tiller is about all that ever develops on regrowth. If the grass is grazed down to Stage 1, then the recovery period will need to be longer.

How Many Times Can a Paddock Be Grazed Per Year?

This depends completely on the growth rate and the time required for recovery. In humid areas with rapid growing conditions and pasture species such as perennial ryegrass and

white clover (which recover very quickly from even severe grazing), a paddock might be grazed as often as every 17 to 21 days during the peak growing season. In severely dry grasslands, it might be desirable to graze a paddock during the growing season only every other year, or every third year, with other defoliations coming during the dormant season.

One rule of thumb is that you can ordinarily graze a paddock once per growing season for every 10 inches of annual precipitation received. As with most of rules of thumb, you should not cling to this religiously, but I have found it to be useful as a general guide in the temperate part of the US where I work.

What Is Overgrazing, and What Causes It?

Overgrazing is like obscenity: It is hard to define, but you know it when you see it. If you live in pastured areas of the world, chances are "overgrazed" is the normal condition for the majority of pastures and rangelands. If you ask a number of people, "What is the cause of overgrazing?" they will almost certainly tell you that the pasture has too many animals on it. They would be incorrect. If that statement were true, then why can so many rangelands be improved while simultaneously increasing the stocking rate? The correct answer is that overgrazing is caused by too many animals in one place for too long and too often.

You Can Bend the Rules, but Don't Violate the Principles behind Them

By observing the rules of rotational grazing, it is quite possible to dramatically increase animals per unit of land area while improving the land area. Any of the rules of rotational grazing can be violated without long-term harm if proper compensation is made. For example, you can graze down severely during a specific grazing event, as long as the recovery period is lengthened to compensate. Likewise, you can return to an area to graze before it reaches Stage 3 (which is how most dairy graziers manage, because it provides a higher quality of pasture forage) if you leave a taller residual, or if you allow a longer recovery period at some point later in the season.

This Beef Is for the Birds!

BLUE NEST BEEF, Cannon Falls, Minnesota

Grassland birds have lost more than 50 percent of their populations in the last 50 years, a steep decline driven strongly by industrial farming practices. The good news, however, is that the grazing management practices that restore bird habitat are largely the same "regenerative grazing" practices that pump carbon back into soil. Dense herds of grazers, moving frequently and not returning to the same spot too often, create the aboveground "structure" on a landscape where different birds want to live. And healthier soil creates diverse grasses and insects that are the foundation of many birds' diets.

Blue Nest Beef is an e-commerce company that delivers, direct to the doorsteps of American consumers, 100 percent grass-fed beef from Audubon-certified bird-friendly land. The Audubon Conservation Ranching Initiative can certify producers up and down the US "Central Flyway" to have implemented grazing practices that regenerate grassland bird habitat.

To become certified, producers must comply with protocols in four areas:

- habitat management
- forage and feeding

- animal health and welfare
- environmental sustainability

On top of this foundation, Blue Nest Beef adds a requirement that the beef is 100 percent grass-fed. The company buys beef from these ranches, processes it, and ships it to American consumers nationwide.

Team of Visionaries

Blue Nest Beef is a creation of Standard Soil, founded by Russ Conser, Todd Churchill, Bill Godfrey, and Allen Williams. The company mission is to escalate the positive impact of regenerative grassland agriculture using the power of commercial business. Russ is an engineer and businessman who spent 30 years in oil and gas at Shell, Todd was one of the earliest grass-fed-beef marketing pioneers, Bill has been one of the country's largest grass-fed finishers, and Allen remains a widely known scientist, practitioner, teacher, and consultant to many farmers and businesses in the regenerative agriculture sector.

In addition, the National Audubon Society engages at least 5 million American consumers annually about the many ways to appreciate and help birds. These bird-loving consumers formed the initial target market for Blue Nest Beef's product. Just like the many partnerships among living things in a prairie, this effort represents a symbiotic relationship between a team who understand the business of regenerative beef production at scale, and a partner

with a strongly aligned objective and their supporters who care.

Blue Nest Beef is just the first foray of a team that is working hard to flip the carbon arrow associated with life on Earth—working to bring more birds back to American grasslands, while putting more carbon back into the ground and better food on American plates.

For more information on Blue Nest Beef, see For Further Reference.

LEARNING BY DOING

The Magic of Moving Livestock Daily

When I began rotational grazing, I thought the perfect system would be to move the cattle on a weekly basis. Since I had a full-time job that kept me on the road during the week, it made complete sense to me to just move the cows every Saturday.

This was one of those classic “looked good on paper” plans that did not work so well in practice. On Saturday and Sunday, the cattle gorged themselves, and I fought bloat. By Friday night, they had eaten all the best plants in their allocation and were down to stems. They were mad and jumping fences. Often, I would come home to broken fences and cattle all over the place. The weaning weights

of my calves dropped considerably, and the most palatable plants in my pasture began to disappear.

I struggled with this for a couple years. Then I attended a seminar taught by Jim Gerrish. He explained, in a manner that finally made sense to me, why daily moves were superior to weekly moves. I was convinced to the point where I made a commitment to daily moves.

Wow. I was in absolute awe at the difference it made. My cattle became content. My weaning weights climbed back up to where they once were. My pasture productivity went up, and the preferred plants stopped declining. It seemed too good to be true. How could something so simple as moving frequency make such a big difference? But it was true.

The improvement in cattle performance was due to dietary consistency. Dairymen know that consistency is critical for milk production, because once the quality of feed drops, so does milk production. If feed quality then subsequently improves, milk production does not recover, and the cows simply convert the excess nutrients into body fat.

The “seesaw” nutritional pattern created by my weekly moves—with very high quality on Saturday and Sunday and poor quality on Thursday and Friday—resulted in very small calves and very fat cows that suffered in the heat and did not rebreed. Moving daily kept the forage quality stable from day to day, so milk production never took a dive.

Distributing Animals Evenly on Pasture

If animals are left to their own free will, they will venture only as far from water as they absolutely need to in order to get enough feed. Research on summer pasture in Missouri by Jim Gerrish indicated that as distance from water increased to more than 900 feet, grass intake dropped rapidly. Shade is usually located close to water in rangeland areas, so animals tend to have very concentrated grazing pressure around these areas. Many ranchers worsen the problem of overgrazing close to water by putting the salt and mineral feeders and fly control devices (also attractive to animals) next to the water source.

One primary goal of proper grazing management is to make animals utilize the pasture area evenly. Rotational grazing can help accomplish this task by confining animals to underutilized areas. Since water is the most attractive feature on the landscape to grazing animals, make water available in underutilized areas. This can accomplish more benefit for pasture vigor than any other practice outside of proper stocking rate. By developing multiple watering points through pond construction, wells, or piping water you can vastly improve pasture performance.

The other way to ensure an even distribution of animals across the landscape is with temporary electric fencing to

confine them to an area that supplies only enough feed to last a day, then moving to the next area (see photographs).

HOW DO DAILY MOVES IMPROVE PASTURE PERFORMANCE?

Daily moves ensure that all plants in a pasture are uniformly defoliated and uniformly rested. Let's see how the two systems —daily and weekly rotations—compare.

With a Weeklong Grazing Period and Three-Week Rest Period

- Animals return to the initial paddock after one complete rotation.
- Some plants will have rested for three weeks (since the last day of the previous grazing period).
- Some will have rested for four weeks (since the first day of the previous grazing period), and some will not even be grazed at all.
- Some plants will be growing back after being grazed. Livestock prefer those less mature, less rested plants, so they graze them more intensively than the better-rested ones.
- With each cycle through the paddocks, these more popular plants continue to get beat up worse and worse. They will lose vigor.
- The other, less popular plants continue to get ignored during future grazing cycles.

With Daily Moves

- Each plant is eaten on the same day, with similar intensity, and is allowed the same amount of recovery period.
- The result is an increase of photosynthesis and yield. This generates more profit and more environmental benefit.
- Because the yield is increased, the number of animals the land area can carry usually increases over time.

This last point is in direct contrast to the common misbelief that the best way to regenerate rangelands is to remove the livestock. This would be a mistake. Not only would that remove a valuable source of high-quality protein from the human food supply, but in order for rangelands to be healthy they need the pruning and nutrient recycling that livestock provides (see sidebar below).

Rangeland Needs Hoofprints to Stay Healthy

Rangelands and herds of herbivores evolved together and are mutually dependent. Ungrazed rangelands, particularly the warm-season grasses found in many hotter semiarid regions, usually experience a degree of degradation if livestock are removed for more than a year or so. The plants produce foliage that senesces in the

winter or during the dry season, and without removal it will shade out the underlying new growth, to the detriment of the plant, because in the dry environment it simply does not degrade rapidly enough.

TIME, LABOR, AND DAILY MOVES

The major objection to daily moves is the additional labor. I found this to be much less of a problem than I expected. With modern tools for electric fencing, such as portable fence reels, plastic polywire, and step-in fence posts, it is possible to take down and reset a 250-foot-long subdivision fence in less than five minutes. (See Figures 11.1–11.3.)

My Method of Persuasion

People often tell me how overworked they are and how they can't possibly make time to move a fence daily. I ask them if they would like to rent the farm across the road from them. Their eyes usually widen, and they say "Yes."

Then I ask if they would still be interested if the rent were free, and the landlord paid all the expenses, as long as they took good care of his land. Their eyes bulge, and they begin to drool: "Yes! Yes!"

Then I tell them, sorry, you don't have time for that extra land. You are too busy. "But, but, but, it is right across the road from me. I could increase my production with no increase in costs, just with some extra work."

And I tell them, that is exactly how daily rotational grazing works. You get a huge increase in production with a 10-minute-per-day investment and, with modern fencing, very little additional costs.

Pasture Management Improves Soil Organic Matter

When pastures and rangelands are managed correctly, the pasture yields more forage, produces more meat, and benefits wildlife. This also pumps more carbon out of the roots in the form of exudates that feed the soil microbes that in turn produce soil organic matter. Proper grazing management is a win for the livestock producer, for the economy, for the food supply, for the climate, and for the environment. There is no sacrifice necessary; proper grazing management improves all the above.

Until recently, precious little research has been done on the impact of different grazing management methods on soil characteristics. The table below illustrates how improving grazing management can improve soil carbon sequestration.

HOW DIFFERENT GRAZING SYSTEMS AFFECT SOIL CARBON SEQUESTRATION

GRAZING SYSTEM	TONS CO_2 EQUIVALENT PER ACRE
Adaptive, multipaddock	188.13
Heavy continuous	105.07
Light continuous	81.09

SOURCE: W. R. Teague, S. L. Dowhower, S. A. Baker, N. Haile, P. B. DeLaune, and D. M. Conover, "Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie," *Agriculture, Ecosystems and Environment* 141 (2011): 310–322.

Restoring Desert Rangeland

ALEJANDRO CARRILLO, Las Damas Ranch,
Chihuahua, Mexico

Here's a common excuse (among many) for not intensifying pasture management: "We don't get enough rain to justify that level of management." After reading what Alejandro Carrillo and his crew have done at Las Damas Ranch in Mexico since 2005, when they began their journey into holistic management, you will see why that excuse simply does not "hold water."

The ranch is in a part of the Chihuahuan desert that receives a scant 10 inches (250 mm) of rainfall a year and has a very high evapotranspiration rate, due to high temperatures almost year-round. Despite the low rainfall, this area was productive grassland in presettlement history, indicating that it could be once again. Severe, unmanaged grazing destroyed much of that grassland, leaving a desert with hard-capped soil ("hard cap") that does not readily allow water infiltration.

What Doesn't Work

Traditional wisdom says that the best way to restore this grassland is to remove all livestock. However, desert rangelands that have been completely destocked for as long as half a century are in no better condition than the surrounding rangelands that are being pastured, and in many cases they are actually in worse shape.

Clearly, removing livestock is not an effective solution. Without grazing animals, grasses shade themselves out. In that arid environment the old grass residue from the previous year's growth does not decay, which prevents the new grass from obtaining sunlight.

What Works

What has been proven effective is Carrillo's approach: a system featuring brief grazing periods with ultrahigh livestock density, followed by full vegetative recovery before the area is grazed again. Rest periods are typically 12 months long, so the grass is allowed to grow a full year before grazing resumes.

When they first began, the ranch was split into 10 paddocks; now they have more than 500. Because most desert grasses hold their quality well during the dormant season, and because the dry conditions minimize weathering losses during the winter, the mature grass can maintain sufficient quality to sustain a cow.

This change in grazing management has completely altered the hydrology of the ranch. The hoof traffic in the paddock breaks up the hard cap found on desert soils, and

with ground cover in place longer, the infiltration rate of the soil has risen dramatically while the rate of evaporation has declined. During the long rest periods the grass roots can fully develop and grow deep into the soil. The intense but brief grazing periods convert a high percentage of the mature grass—which would otherwise just oxidize away in the brittle environment—into manure to nourish the soil.

This improvement in both the amount of water stored in the soil and the increase in vegetation has even resulted in an apparent rise in local precipitation. All of these factors have resulted in significantly higher carrying capacity and more animal product produced by the ranch.

Learning Curve

Carrillo says they have learned a lot along the way and made a few mistakes. One of the biggest: beginning with inadequate drinking water for the number of animals their ranch would eventually be able to carry. They started with 1.25-inch water pipes, then moved to 2-inch and now to 3-inch water pipes to provide drinking water to all their paddocks. They now have 20 watering storage locations around the ranch.

In addition, he said, it was critical to have good, low-maintenance genetics. They give no external inputs to their animals, and individuals that do not thrive in their system are quickly culled.

He is now pleased with their progress and plans to keep on course, working with nature and watching the ranch continually improve. When you see the lush Las Damas grass and compare it to the bare soils of most ranches in the area, it is easy to see why they are happy!

Strategies during Droughts and Other Emergencies

There will be times when you need to be flexible. The standard method of maintaining flexibility is quite simple: Have a supply of stored feed (such as hay or grain) on hand, and feed this when the supply of forage begins to fall behind. There are, however, additional strategies available.

Feed Hay or Grain

It is essential to have a "sacrifice pen," completely removed from the pasture, where you can feed livestock. Otherwise, they will continue to graze every last nibble of green grass in preference to the dry hay. It is far better to feed a little hay early, so that pastures have a chance to recover early, than to allow the pastures to become abused and have to feed a *lot* of hay later.

Even on good pasture, most animals will eat a pound or two of dry hay each day. In a rotational grazing system, allowing

free-choice hay at all times gives an extra safety measure in case the move from one paddock to the next comes too late for either the animals or the grass's vigor. Feeding hay should not, however, be used to maintain animals on a pasture once they have grazed it below targeted residual grazing heights; that will quickly ruin it. It is better to move them to a small sacrifice area and feed hay there.

In contrast, animals prefer grain to pasture. You can feed it in small quantities if pasture growth is slightly deficient, but avoid feeding large quantities to ruminants on pasture. Consuming grain at high levels (more than 0.5 percent of body weight daily) can acidify the rumen due to the rapid fermentation of the starch in the grain. This can interfere with forage digestion, since the microbes that digest forage are killed when the rumen becomes acid.

Distillers' grains, wheat midds, flaxseed, and soybean hulls are feedstuffs that are high in energy and are very palatable but do not contain starch and thus do not have this acidifying effect. They can be fed in larger quantities than grain as a pasture supplement without ill effects.

One of the wisest ranchers I have ever met keeps part of his carrying capacity as cows and the rest as steers. If a drought occurs, the steers go to sale early.

Reduce Herd Size

The opposite approach is to reduce the number of animals as it becomes apparent that forage supply is dwindling. As obvious as this seems, it is rarely done early enough. This is because most livestock operations consist solely of reproductive animals, such as a cow-calf operation. Getting rid of a mature reproductive female is very difficult. That girl is your future cash, and she is hard to part with, even if keeping her destroys the pasture she depends on. It is human nature to keep reproductive animals far too long.

On the other hand, growing animals, such as stocker steers, are intended to be sold at some point anyway. Taking cows to a sale is a sad day; taking stockers to the sale is a good day. One of the wisest ranchers I have ever met keeps part of his carrying capacity as cows and the rest as steers. If a drought occurs, the steers go to sale early. He maintains just enough cows to match forage supply in the worst drought and keeps enough steers on hand to eat the rest of the forage in the better years.

Extend Pasture

Another way to maintain flexibility is to add in extra pasture area during short periods. Some ranchers hay surplus feed during the spring flush of growth, then turn animals into these acres after regrowth has occurred. Another method is to seed cover crops into the stubble of harvested crops and pasture these areas when perennial pastures are nonproductive.

This is such a successful strategy that I believe it should be a yearly practice wherever croplands and pastures are

intermingled. Most perennial pastures are most productive in late spring and early summer, with less production in late summer and fall, and usually nonproductive in winter.

A final method is to "stockpile" feed in pastures for later use. One can either reserve areas that are ungrazed for a long period (to act as a reserve grazing area) or "top" pastures off with light grazing during surplus periods and graze to shorter residuals during less productive periods. With the latter approach, the reserve feed is simply the bottom several inches of pasture growth. With few exceptions, however, forage that is left to stockpile becomes less nutritious as it matures.

Profiting during a Drought

These ideas can also be a way to expand in hard times. The rule to becoming wealthy in any business is quite simple: Buy low and sell high. Yet the decisions we normally make in the cattle business usually force us into selling low and buying high. This is because, in a drought, either we have to sell breeding females when there is zero demand for them (because everyone else is also trying to sell) or we have to buy feed when feed is outrageously high. Here are some tips on how to profit from a drought:

- Buy surplus hay when it is in surplus—and cheap—because no one wants it at that time. Put it in a barn and hold onto it; you will need it soon enough.

- Maintain part of each herd as stocker animals and part as breeding females. When forage becomes short, sell the stockers, because they keep their value in short-forage conditions (see Stockers Offer Flexibility below).
- Feed the breeding animals you purchased on the cheap with your previously purchased cheap hay. When pasture conditions return to normal, you will often be able to double your money on these animals because those who destocked will be eager to refill their pastures.

Stockers Offer Flexibility

The value of stockers depends largely on the value of meat, which does not decline in a drought, and on the price of grain, since most of these animals are primarily marketed to feedlots. The price of grain is determined on a global basis by the Chicago Board of Trade (rather than locally the way hay and breeding animals are) and will go up only in a prolonged nationwide or worldwide drought. Hay, on the other hand, becomes expensive in a localized drought. That is why you stock up when it is cheap.

In Kansas, during the hard winter of 2018 to 2019 and following the drought of 2018, hay was outrageously expensive in Kansas. I had to buy some for $170 a ton to make it completely through the winter. At the same time, hay in the eastern US was bringing $20 for a 1,200-pound

round bale. The price of corn was about the same the country over, and so was the price of calves. The price of those two commodities is based on global conditions, not local conditions. Cows, though, were about worthless in my area because no one had hay to feed them.

Had I taken my own advice, I would have had a barn chock-full of hay purchased a couple of years earlier when it was ridiculously cheap. I could have sold my stockers to generate some cash, then turned around and bought some of the dirt-cheap cows that were for sale that spring.

Can We Feed the World with Grass-Fed Meat?

DALE STRICKLER, Kansas

The fastest way to increase the carbon content of a degraded soil is to establish a perennial grassland and graze it with ruminant animals in a proper manner. This fact has been well established both by scientific research and by centuries of practical experience.

What happens, though, when anyone proposes that we convert large areas of degraded cropland to pastures, in order to sequester enormous amounts of soil carbon? Detractors say that to do so would cause worldwide starvation, since statistics based on current levels of pasture production indicate that a pasture typically produces much smaller caloric output than a typical crop field.

Eight Ways to Improve Nutrition by Improving Pasture

That isn't the entire story, however. Here are some points to keep in mind.

First of all, throughout history the best soils were converted to cropland, while the worst soils were spared

the plow and left in pasture. Most pasture acres simply cannot grow crops, because they are too rocky, too shallow, too droughty, too flood-prone, too something to grow crops. Pastures placed on productive ground are often several times more productive than the average pasture.

Second, the average cropland is relatively well managed, while the average pasture receives virtually no management: The animals are simply turned out and left to fend for themselves. When a controlled system of grazing management gets underway, even these current pastures on poor soil unfit for cropland can have their meat output doubled or more.

Third, cropland usually receives massive inputs of fertilizer and pesticides produced from finite mineral deposits or petroleum, and field operations usually involve petroleum-guzzling machinery. Pastures can be quite productive with no petrochemical inputs; biological processes can provide all the fertility needed.

Fourth, it is quite possible for an area of land to produce both a pasture crop and a grain crop in the same year. One example is the pasturing of animals on the crop residue left after a grain harvest, such as cornstalks. Although low in protein, crop residue is quite abundant, and in the United States only a small fraction of it is grazed. What if all of this material were utilized? The meat thus produced detracts not one kernel from the preceding grain harvest; rather, it is an addition to the world protein supply.

A fifth practice is to plant cover crops on cropland between grain crops. For example, a cover crop of rye can be planted after corn harvest and before soybeans are planted the next year. The corn and soybean crops occupy the ground for only 4 or 5 months of the year. For the remaining 7 or 8 months, the rye soaks up all that otherwise wasted sunlight and converts it into high-protein vegetation in the winter, when quality pasture is most often lacking. The rye also makes a nice protein supplement to the low-protein residue.

A sixth approach is pasture cropping, or planting a grain crop into existing pasture land. (See the profile on Colin Seis and the one on Dan DeSutter.) The grain crop is selected to have the opposite growing season of the pasture—Colin grows winter cereals such as winter oats in his warm-season grasslands, and Dan grows corn in the summer in his cool-season bluegrass and white clover pastures. This system produces a grain crop, offers animal grazing after the grain harvest, protects the soil from erosion, and builds soil carbon.

Seventh, comparing bulk calories produced in cropland versus pasture seldom takes into account the nutritional density of meat compared to grain. For example, corn produces an insane amount of calories per unit of land area (if it has large amounts of fertilizer) but not much else in the way of nutrition. It is basically starch, with a very low content of amino acids, minerals, or vitamins. Meat, on the other hand, is rich in almost every nutrient a human needs. Our world as a whole experiences far more protein deficiency than lack of calories. This is why we went down

the road of feeding corn to livestock, to take advantage of the nutritional upgrade you get when corn is converted into meat.

Eighth, the food produced from pasture is not limited to the meat or milk coming from the grazing of livestock alone. Unlike cropland, which displaces wildlife, pastures offer phenomenal wildlife habitat, and much of this wildlife can be harvested. A well-managed pasture will have an abundance of birds, wild ruminants such as deer and antelope, rabbits, wild pigs, and, if you aren't picky, a lot of reptiles, amphibians, and insects. Ponds for watering livestock can also produce fish, mollusks, crustaceans, or amphibians for food (if you have never tried crayfish or frog legs, you are missing out). The trees that provide livestock with shade can be fruit or nut producers and can even become a planned crop (see Chapter 12). I fondly remember collecting wild blackberries, mulberries, and gooseberries from pastures in season. (There is no better pie made than a gooseberry/mulberry pie.)

All told, there is enormous potential for producing grass-fed meat without decreasing the amount of crops grown for human consumption.

CHAPTER 11 SUMMARY

- Of all terrestrial ecosystems, grasslands have the most potential to rapidly store soil carbon.
- Well-managed grazing involves maximizing photosynthesis, which will simultaneously improve soil carbon and production of meat, milk, or wool from the pasture.
- There are three parts of the grass life cycle: vegetative, reproductive, and dormant.
  - Vegetative grass is the most nutritious to grazing animals and has a moderate tolerance of grazing.
  - Reproductive grass has moderate nutritional value and low tolerance of grazing.
  - Dormant grass has low nutritional value but is very tolerant of grazing.
- Continuous grazing is the most common grazing system, and results in very good animal performance, but requires a low stocking rate to maintain that animal performance for a long period of time and to prevent pasture degradation.
- Rotational grazing of various forms allows for more control of grazing severity and residual vegetation left at the end of a grazing period, more control of uniformity of grazing pressure, and more control of recovery period. When

rotational grazing is practiced in conjunction with intelligent planning and timely adjustments (often referred to as holistic or adaptive management), then it can be a powerful tool for rangeland improvement.

- Drought planning should be incorporated into any rangeland management scheme. Stored forage, planned emergency grazing, and strategic destocking should all be part of the plan.

12

Agroforestry

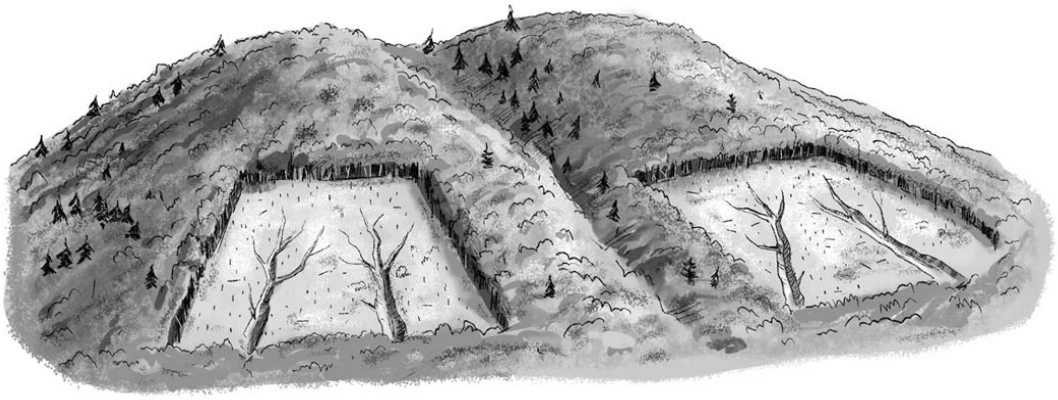
In the early part of the 20th century, a geographer named J. Russell Smith traveled around the world and took note of the conditions of both soil and society in a number of different areas. He observed the devastating soil erosion associated with annual grain crops and, in contrast, the food systems based on trees that dropped fruits and nuts that were harvested by either humans or livestock. He noticed that societies based on tree crops were prosperous and long-lived and did not require the backbreaking work associated with growing annual grain crops. In addition, the soil was held intact by the trees and did not require land-ruining tillage.

Trees Instead of Grains

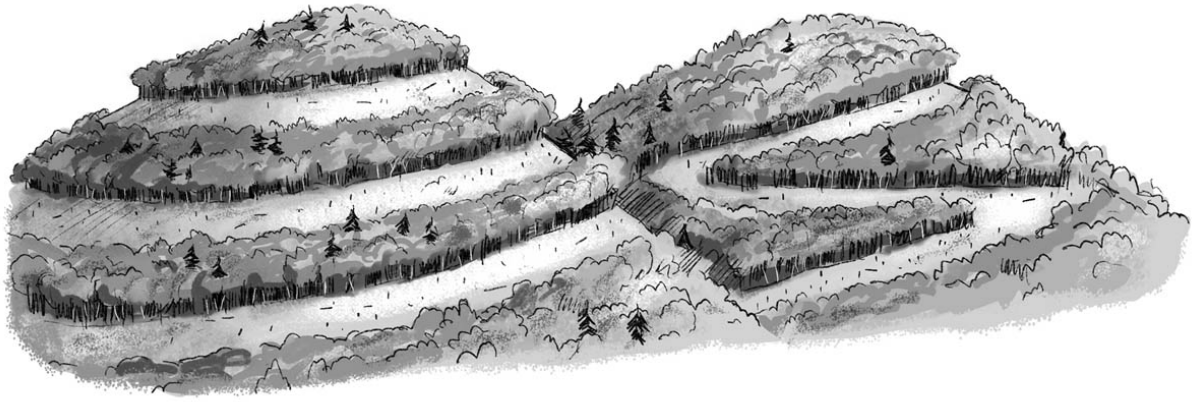
Smith detailed his observations and ideas in the book *Tree Crops*. I read the book when I was in college, and it completely altered my view of what the future of agriculture should be. The focus of Smith's work was trees that feed not humans, but livestock, by replacing grains with fruits and plants. The practice of pasturing the herbaceous understory of a plantation of widely spaced trees with livestock is now called **silvopasture**.

Smith lists several trees that could be cultured to replace corn or soybeans in livestock diets. The fruits and nuts from these trees could be harvested by the livestock themselves, without any labor required for annual planting or harvest or

weed control. He envisions farms with tree species that drop fruit in succession to feed the livestock pastured on the understory of grasses and legumes below.



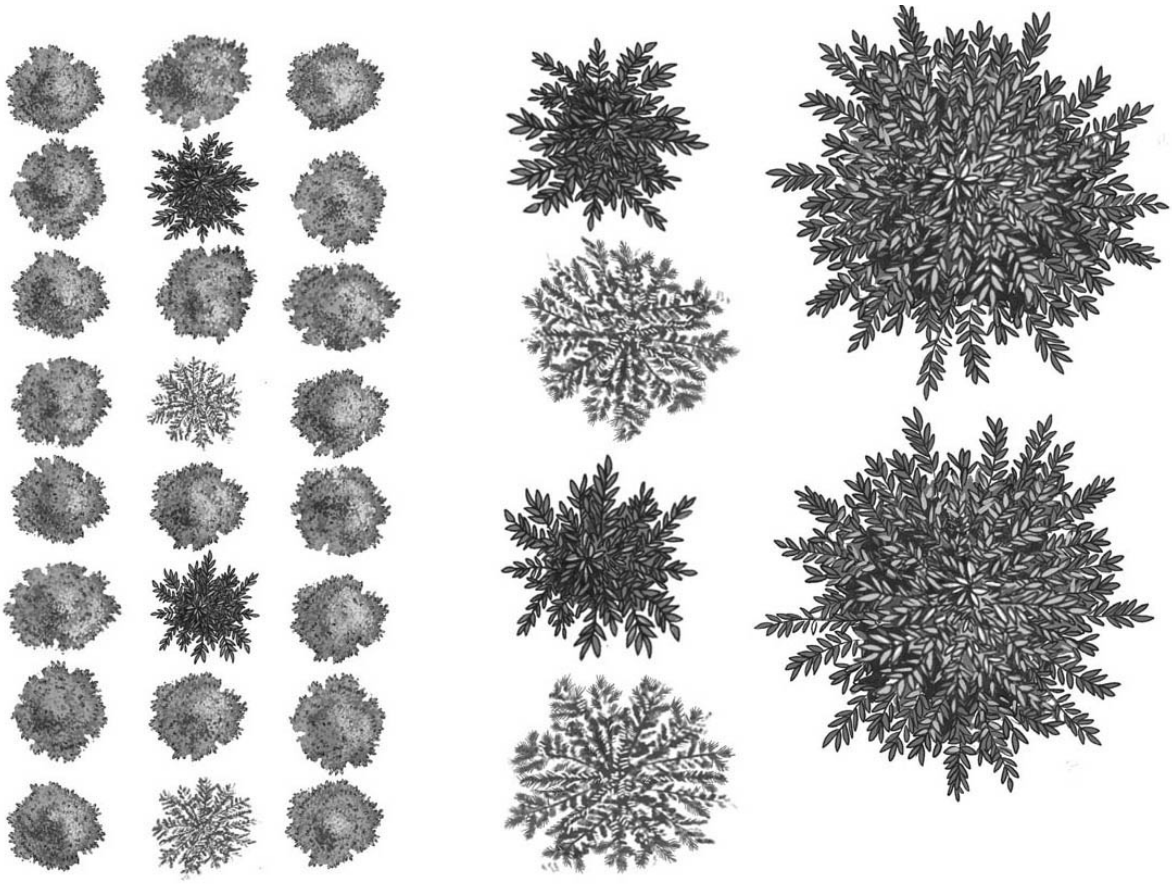
ABOVE: *Large blocks of clear-cut expose soil to erosion.*



ABOVE: *Thin strips of clear-cut along the contour reduce soil erosion.*

For example, mulberries could provide summer fruits for swine or poultry, and persimmons, apples, and pears could drop fruit for livestock to browse in the fall. Dry fruits from chestnuts and oaks (both high in carbohydrates) and nuts from hickories, walnuts, pecans, and hazelnuts (all high in oil and protein) could extend the duration of food availability into the winter. Thornless honey locusts could drop pods useful for cattle feed in the winter, to replace the corn fed to cattle in feedlots.

It is a sad commentary that three-quarters of a century after Smith's landmark work, so little has been done to make his vision a reality. Imagine how different our country might be if the 95 million acres of corn and the 90 million acres of soybeans were instead in a mixture of grass and trees, dropping feed freely picked up by livestock.



ABOVE: *FROM LEFT TO RIGHT: Prior to first thinning; After first thinning, black locusts are removed for fence posts and firewood.; After second thinning, pines are removed; only high-value hardwoods remain.*

Black locust, a rapid-growing leguminous tree

High-value hardwood trees (black walnut, oaks, black cherry, etc.)

Pines for pulpwood and construction lumber

LEARNING BY DOING

An Orchard for Livestock

I once rented a pasture that adjoined a yard containing two apple and two pear trees. Every fall when the fruit ripened, the loaded trees would drop any blemished fruit early. The homeowner hated mowing around the fallen fruits, and my cows liked to eat the ones that rolled across the fence, so when they were in the adjacent paddock I would throw the windfall fruits across the fence. At other times, I would fill my pickup bed and drive the fruit to where the cows were. It was a great win-win method to clean up the yard and give my cows a treat at the same time. Every morning for about a month, out of just four trees, there was a pickup load for my cows, and the feed came at a time when pastures were starting to get rather bare.

But it was time-consuming and backbreaking work. I thought, what if, instead of doing all this work, I planted apple and pear trees right where I needed the fruit to be: in my pastures? They could give my cows shade in the summer, fruit in the fall, and fallen leaves in the winter as forage. Instead of just four trees for the entire herd, I could have a tree spaced every 30 or 40 feet on a grid, 30 or 40 trees per acre. Now that would feed a lot of cows!

Given that my 100 cows on that pasture usually had about 2 acres of daily allotment, each cow would get to eat the windfall from roughly one tree in addition to the usual ration of grass and clover growing below. Also, every day I would get to pick a few to munch on myself! And all this production came as a complete bonus to the yield of the pasture forage below, since the widely scattered trees don't harm the grass at all. At 30 trees per acre, and an average dry matter yield of 80 pounds per tree, that is an extra 2,400 pounds per acre of high-energy feed, on top of the usual 2,000 pounds or so of pasture produced per month of prime growing season.

It was observations like this that led J. Russell Smith to write *Tree Crops*, and the observations are just as valid today.

Agroforestry in a Nutshell

Smith's idea is an example of a little-used system of agriculture called **agroforestry**. It's easiest to explain if we start with forestry. Forestry is essentially the cultivation of trees: Trees are the primary crop, usually intended for timber harvest. It is often the sole enterprise on many timbered lands. Agroforestry, on the other hand, is the culture of trees integrated with other forms of agriculture, such as pasture or crops.

Agroforestry has many advantages over simply using the land for a single purpose, whether that purpose is forestry, livestock, or crops. Some of these advantages are:

- The vegetation can capture sunlight over multiple layers and for an extended season. More photosynthesis means more productivity and, ultimately, better soil.
- Tree canopies can protect underlying crops and animals from sun and wind.
- Tree roots and herbaceous plants underneath can combine to reduce soil erosion from either wind or water.
- Increased plant diversity reduces the risk that a disease or insect can take out the entire crop. At the same time, that diversity will attract a wider range of benign insects, which attract insect predators that, in turn, can then control future pest insects.
- The risk of low prices for any one enterprise is reduced; the portfolio is more balanced.
- Diversity of crop roots and the extended duration and increased rate of photosynthesis improve the rate of carbon sequestration in the soil compared to that of forest, grass, or cropland. In fact, silvopasture is regarded by many soil scientists as the terrestrial land use with the highest rate of carbon sequestration of all agricultural systems.

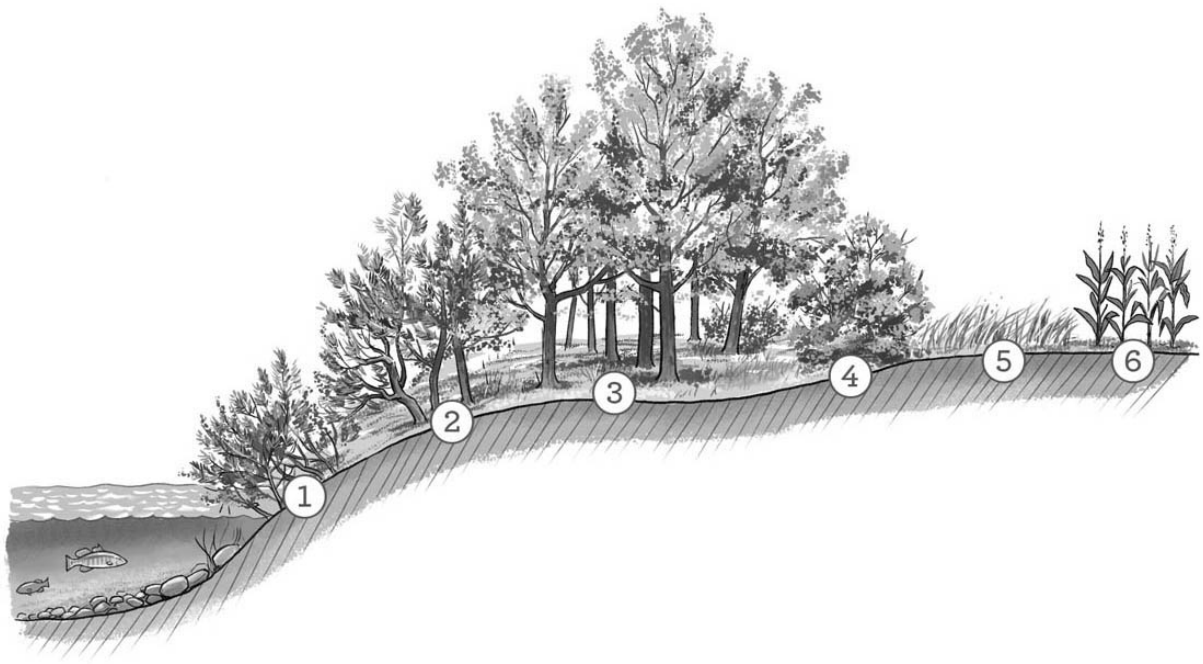
Agroforestry Practices

The following are the primary forms of agroforestry.

Riparian Buffers

By protecting the banks of streams and rivers from soil erosion, riparian buffers not only save soil from being lost, but they also reduce the amount of pollution in water from soil particles, pesticides, and fertilizer. A properly designed riparian buffer should consist of trees, shrubs, and herbaceous vegetation to fully protect soil and water.

You can select species of trees to provide a harvestable crop, such as maples for syrup or walnuts or pecans for nuts and timber. Many high-value trees such as black walnuts and pecans are natural inhabitants of riparian areas. An example of a riparian buffer is diagrammed below.



ABOVE:

1. Water-tolerant shrubs (willow, buttonbush, etc.)
2. Flood-tolerant trees (pecan, pin oak, bald cypress, etc.)
3. High-value timber trees (black walnut, white oak, black cherry, etc.)
4. Upland shrub transition zone
5. Native grass buffer
6. Crops

Windbreaks

Valuable in countless ways, windbreaks can be used to protect homes, crops, or livestock. Their design—the location, spacing of trees, and number of rows—varies by the intended purpose, as seen in the diagram above.

Home protection. In areas with cold winds and winter snow, windbreaks trap snow, reduce wind velocity around homes, and reduce home heating costs.

Livestock protection. Windbreaks for livestock can greatly reduce winter feed needs and improve comfort as well as reduce animal mortality from blizzards. They should be located perpendicular to prevailing winter winds, and on the windward side of the animals.

Crop protection. For crops, the windbreak is usually placed on the windward side of prevailing hot summer winds. Sometimes trapping snow is important for increasing moisture supply; for this, the windbreak should be on the windward side of the prevailing winter winds.

Windbreak Architecture

ABOVE:

1. Strong winds are diverted over the windbreak.
2. Wind velocity through the windbreak is greatly reduced.
3. Area of still air for livestock comfort.
4. Snow is deposited where wind is slowed.

Forest Farming

The cultivation of crops that thrive in a forest environment is called forest farming. (See Figure 12.4.) The best-known high-value forest product is maple syrup. Many other trees, such as

birch, sycamore, walnuts, and hickories can also be tapped for sap that can be boiled down into syrup, each with their own unique flavor.

Other examples of forest crops are medicinal plants, such as ginseng, black cohosh, and goldenseal; mushrooms, such as shiitake; and fruits, such as pawpaw and currants. (See Figures 12.1–12.3 and 12.5.) Truffles are an underground fungus of particularly high value.

Alley Cropping

Common in tropical areas, alley cropping is the practice of planting rows of trees on a wide spacing alternating with rows of crops in between. (See Figure 13.1.) It can be a long-term strategy, or it can be a transition stage prior to silvopasture, when trees are small and unable to withstand livestock browsing or rubbing.

Many silvopasture projects begin as alley cropping with tree rows spaced out to allow a planter or combine to pass between the tree rows. As the trees grow, they often begin to shade the underlying crops and interfere with tractor and combine use. At this time, it may be prudent to sow the row middles to pasture. Once the trees reach this stage, they also are becoming more tolerant of livestock rubbing and the branches are out of the reach of livestock browsing.

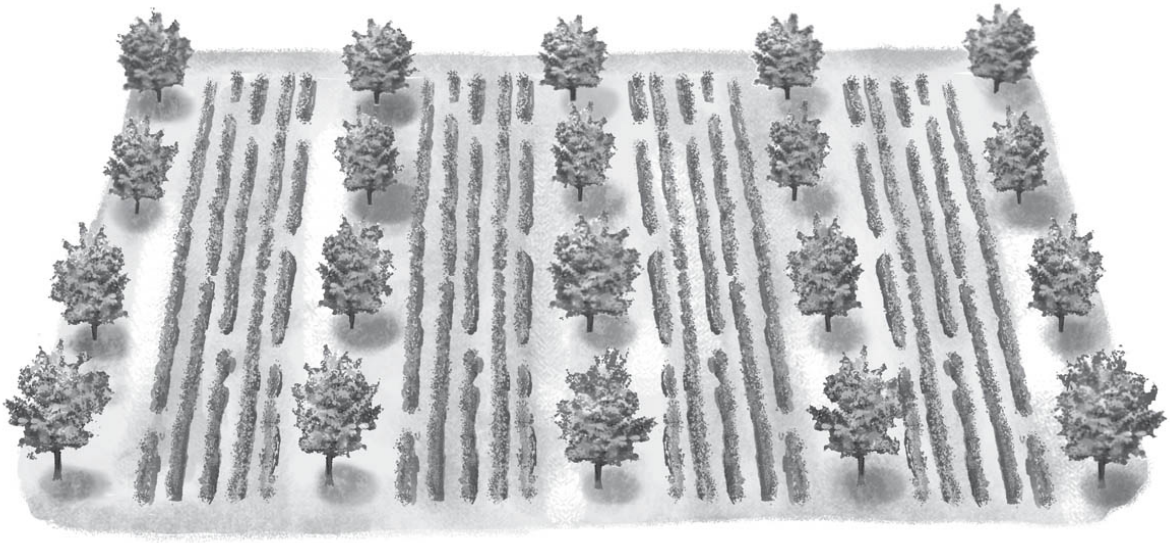
Crop protection. Alley cropping can benefit the row crops by protecting them from wind, especially in areas where sandblasting of crops is common due to windblown soil, or

where evapotranspiration is high due to frequent strong winds.

Natural mulch and fertilizer. In tropical areas, alley cropping involves leguminous tree rows alternated with annual crops. The farmer cuts off the tree branches after the crop is established and uses them as a mulch between the crop rows to protect the soil from the hot tropical sun.

The mulch also releases nitrogen as it decays. This is a very useful practice where nitrogen fertilizer is expensive and hard to obtain by subsistence farmers.

Alley Cropping Layout



ABOVE: *Alley cropping offers multiple land management benefits. The basic configuration—the "corrugated canopy" of alternating tall trees and short crops—effectively captures sunlight and leads to a high level of biological productivity. The ground-level (often annual) crops are productive in the short term and help the land provide immediate returns, while the trees are a long-term crop that may take several years to become profitable. Other benefits include shade for livestock, windbreak capacity, and increased biodiversity.*

Returning Chickens to their Roots

REGINALDO HASLETT-MARROQUIN, Northfield, Minnesota

All domestic poultry are domesticated versions of wild birds that foraged their sustenance entirely from the wild. Chickens descended from jungle fowl native to India, turkeys from the wild turkeys of North America. When these birds were first domesticated, they lived as their wild ancestors did, scratching out an existence, roaming about the farm, scooping up seeds, vegetation, and insects. Any meat or eggs the fowl produced were simply bonus food for the farmer.

But raising free-range poultry also had its drawbacks. While the meat and eggs were free meals for the farmer, they were also free meals for other animals. The loss of poultry to predators led eventually to the indoor confinement of birds—at first only at night, but ultimately full time.

Once birds were indoors 24 hours a day, farmers had to provide the birds 100 percent of their feed. The era of "factory farming" had arrived, and birds were now entirely separated from what had originally made them a "free" food on the old farmstead: the seeds, greens, and insects.

Best of Both Worlds

Fast-forward to today, when some innovative food producers are developing systems where a good portion of their poultry's diet comes from the space in which they roam. Such a producer is Reginaldo Haslett-Marroquin, a native of Guatemala who now lives in Minnesota. Reginaldo's setup imitates the habitat of the original jungle fowl, with a polyculture of fruiting and nut trees and shrubs that provide a multitude of benefits over an extended period of time throughout the season.

In his system, birds are rotated—following a well-tested and proven protocol—among paddocks that have native elderberries and hazelnuts as the foundation of the understory, and oaks and other trees as the overstory. The shrub layer provides some protection from avian predators, and a perimeter fence provides protection from four-legged predators. At night birds come indoors for additional protection from predators and cold Minnesota night temperatures.

Though still given a grain ration, the birds can glean a good portion of their diet from their forestlike surrounding. The ground-level scratching area is managed with a multitude of perennial and annual forages (mostly high-protein, low-fiber broadleaf species) plus sprouted grains spread in the field. In some experimental flocks this combination has provided 100 percent of the daily food intake for up to four weeks, depending on the farm's state of development, farmer training, availability of grains, age of the birds, and weather conditions.

Two separate ranges allow some rotation of the birds. After a brooding period of 4 weeks after hatching, the birds are allowed to roam in the ranges. Broilers are run until ready for harvest at 60 to 70 days, while layers begin laying at 18 to 22 weeks and continue until 85 to 90 weeks.

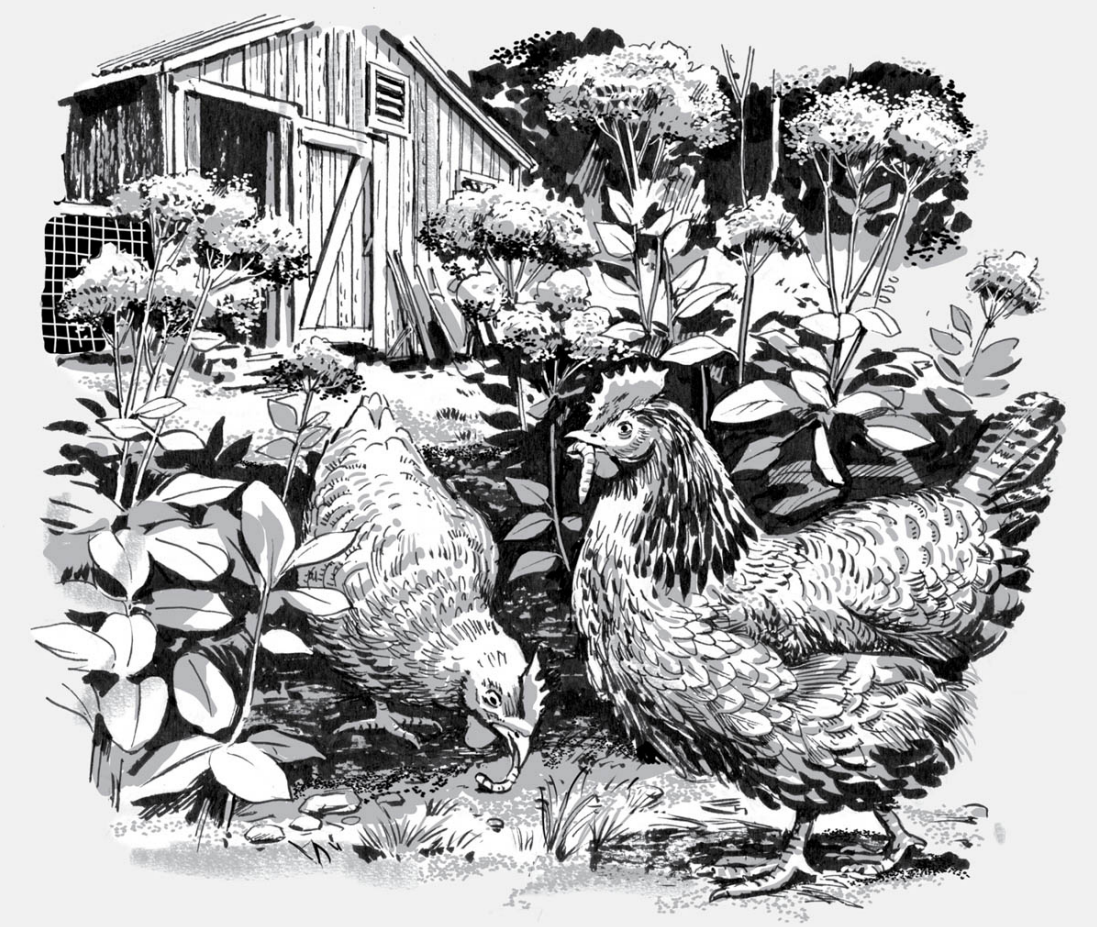
Multiple Benefits

The layering of the vegetation provides excellent capture of sunlight, compared to that of a corn or soybean field, and the perennial root systems and vegetative cover increase soil carbon sequestration and virtually eliminate soil erosion. The lower temperature at ground level, higher humidity, and increase in organic matter create an ideal environment for sprouting grains. In turn, the grains can provide a healthier food source, higher value for the grain, better conversion-rate outcomes, lower health issues, and fewer losses.

The integration of poultry with the vegetation also greatly aids insect control, because pest insects simply become free feed for the birds rather than a nuisance that requires spending money to control. The bottom line is a pasture that provides not just green feed for the poultry, but also feed to replace grain and protection from predators.

Reginaldo Haslett-Marroquin directs the Regenerative Agriculture Alliance. He is cofounder of Regeneration Farms, home of Tree-Range™ Chicken, and author of *In*

the Shadow of Green Man, the story of his journey from poverty and hunger to food security and hope.



Silvopasture

The integration of trees and pasture, silvopasture essentially mimics a savanna, an ecosystem that arguably produces more animal biomass per unit of land area than any other on Earth. (African savannas—those that still exist—host spectacular

animal populations.) You can create a silvopasture by adding trees to a pasture, or by adding herbaceous vegetation (grasses, legumes, and forbs) to a forest.

Benefits of Silvopasture

The incredible potential productivity of a silvopasture arises from several factors.

SUNLIGHT CAPTURE

Trees and pasture together can capture sunlight over a longer duration than either can alone. Multiple layers of leaves and the "corrugated canopy effect" (more leaf space in the same unit of land area) increase this capacity. (See Chapter 7.)

For example, evergreen pine trees with an understory of warm-season grasses will photosynthesize at a high rate both in summer (due to the efficient C_4 photosynthetic capacity of warm-season grasses) and in winter (from the pine trees that keep their leaves, or needles, in winter).

A combination of deciduous trees and cool-season grasses takes advantage of the trees getting first use of the light in the summer, with the shade-tolerant C_3 grasses underneath. In the fall the trees drop their leaves and allow more light to reach the grasses during winter, when sunlight is less direct and available, until trees leaf out in spring.

ANIMAL PRODUCTIVITY

Silvopasture can protect animals from intense heat and sun in summer and from wind in winter. Research in Kentucky has indicated that in the summer, in humid areas, shade can increase animal performance to a remarkable degree, increasing average daily gain on beef steers by 1.25 pounds of liveweight gain per day.

It is also well documented that wind protection can increase animal performance in winter. Specific tree species can be planted to provide dropped leaves in the fall for supplemental livestock feed at that time, or dropped fruit or nuts for even more livestock feed.

PLANT DIVERSITY

A diversity of plants confers countless benefits, such as these:

- Diversity reduces disease and insect pressure on any one species of plant.
- The mix of roots, root exudates, and vegetative material returned to the soil increases soil development and productivity.
- Woody debris and fallen leaves are particularly valuable for the development of soil fungal populations, while herbaceous perennial plants also are highly beneficial to soil.
- A combination of grasses, legumes, forbs, and trees can build soil much faster than any of the components individually.

Some species of trees, such as oaks and pines, host ectomycorrhizal fungi, which are different from the

endomycorrhizal fungi hosted by most herbaceous plants; the former are highly capable of boring into the rocky soils that characterize many pastures and extracting water and nutrients from the soils. This explains why many rocky areas are dominated by oak and pine trees. The cycling of the nutrients thus extracted and contained in needles, leaves, and acorns can help enrich soils beneath them to the benefit of the other plants. (See Figure 12.5.)

Silvopasture Management

Because silvopasture management must take into account the needs of pasture, trees, and animals, it demands more thought than most land use. That means more careful planning, closer monitoring, and more ongoing maintenance. For example:

Protect trees from animals. When trees are small, they may require protective structures to prevent animals from browsing and rubbing on them. Rotational grazing might also be essential to minimize damage to trees and tree roots. You can also incorporate tree lines into electric fence lines of paddock subdivisions, managing the fencing to minimize livestock eating and rubbing on trees.

Choose shade-tolerant forages (that are fairly noncompetitive with the trees). For example:

- Among warm-season grasses, eastern gamagrass is more shade tolerant than most other species.

- Among cool-season grasses, Virginia wildrye is very shade tolerant but may be less productive than other species, such as low-alkaloid reed canarygrass or orchardgrass.
- Among legumes, kura clover (or AberLasting clover, which is a hybrid of kura and white varieties) is a star; subterranean clover also is good.

Control competitive plant species. Tall fescue and smooth brome are notorious for being competitive with trees, especially in early development. This is not to say that these species cannot be used in a silvopasture (and they may have advantages that other forage species do not), but you must manage them.

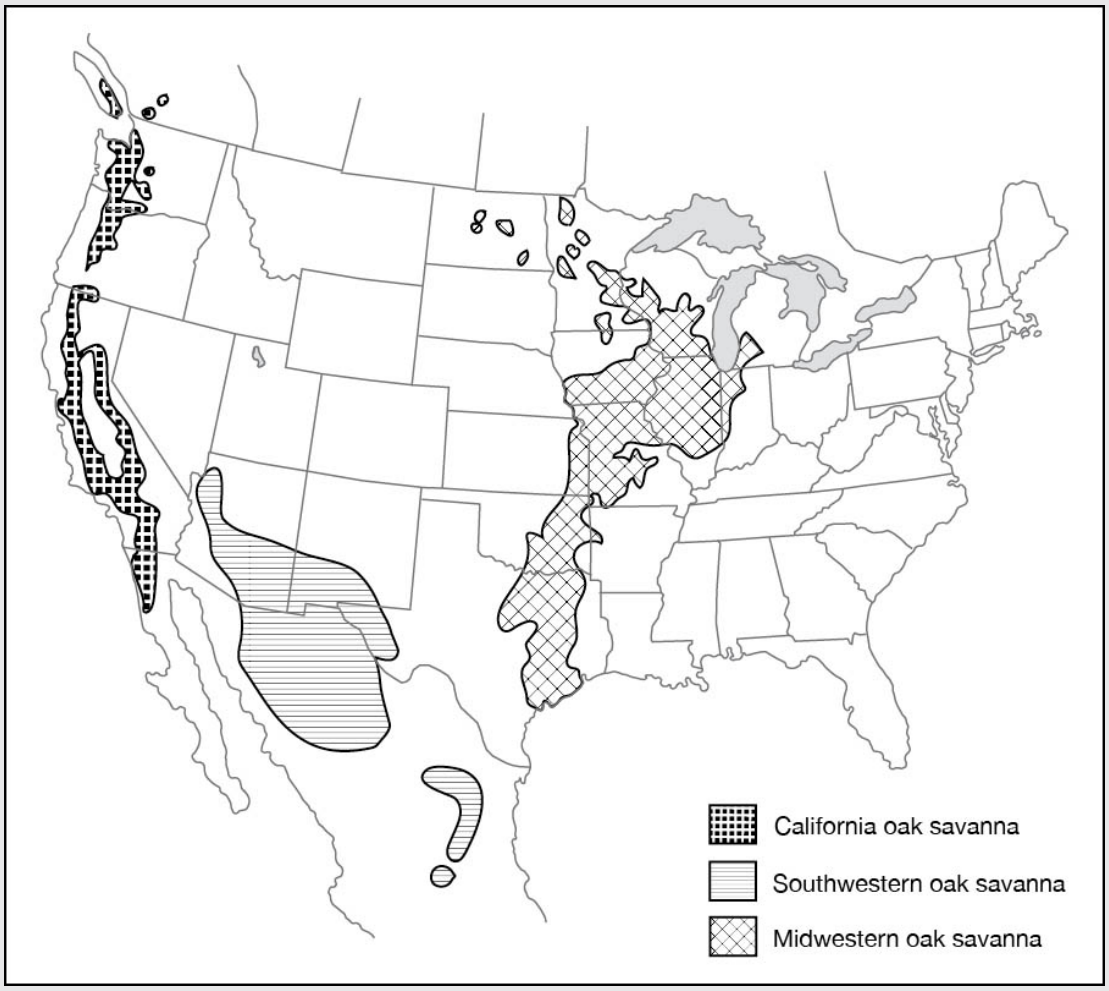
For example, maintain a grass-free area around the bases of the trees; or plant shallow-rooted white clover (or maybe currants, ginseng, or goldenseal) for a higher-value shade-tolerant crop. Grass can be selectively removed from broadleaf plants or legumes with the herbicide Clethodim, if the landowner is not opposed to herbicides.

American Savanna

What was once the North American savanna has now unfortunately been almost completely converted into cropland. The underlying soils were typically very deep and productive, largely due to the ability of a blend of

trees, grasses, and grazing livestock to sequester carbon and nourish soil-generating microbes.

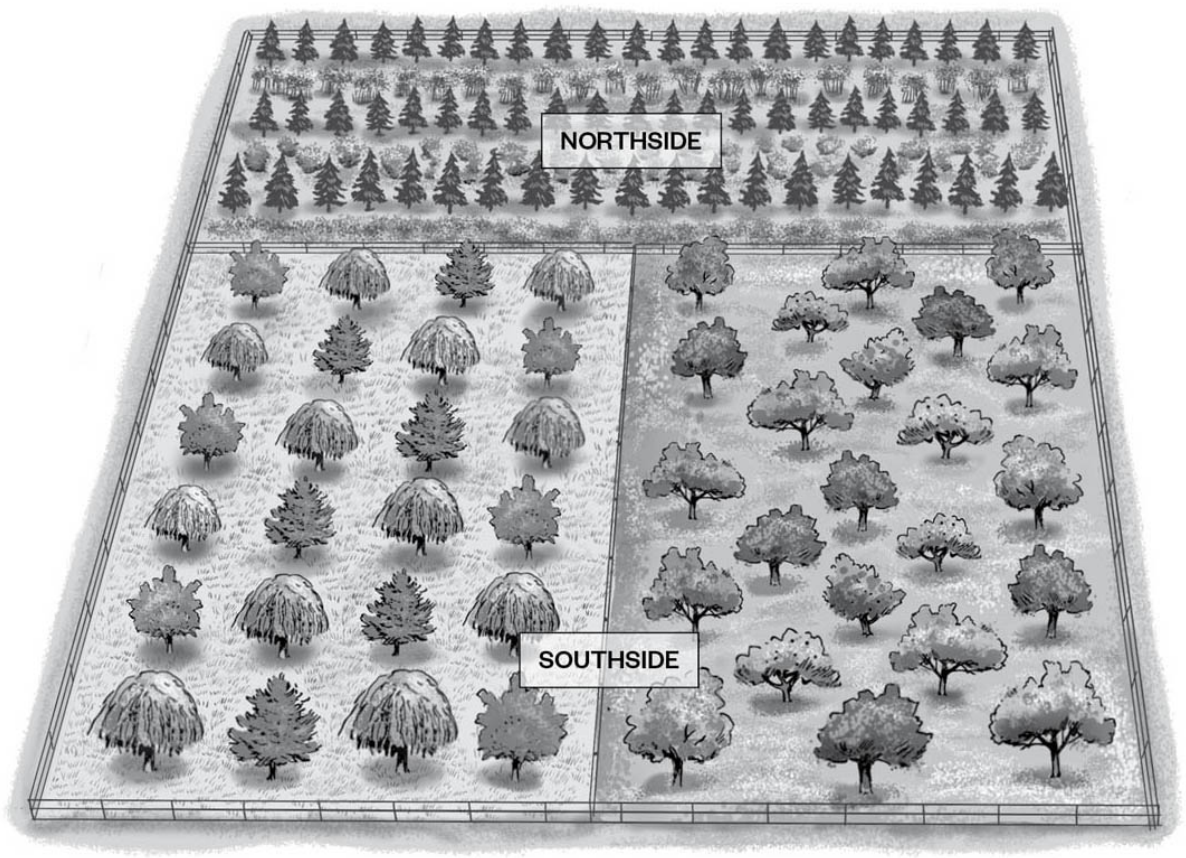
Source: Savanna Oak Foundation, www.oaksavannas.org



My Dream Silvopasture Farm

I have already described how much the book *Tree Crops* influenced my thought patterns. After being inspired by J. Russell Smith, I have sat down many times over the years to sketch out an ever-evolving plan for my future silvopasture farm.

I want a high percentage of the farm to be perennial vegetation, which would provide year-round grazing for a beef cow herd and drop a sequence of fruits and nuts to be harvested by pigs and poultry. The plan includes three distinct pasture types.



ABOVE: *TOP:* **Winter pasture area.** *Coniferous tree rows are perpendicular to prevailing winter winds. Understory forage species are selected to retain quality in winter (such as tall fescue, wildryes, four-wing saltbush,* Bassia prostrata*).*

BOTTOM LEFT: **Summer pasture area.** *Tree rows are parallel to summer wind so animals can find areas throughout the day that are both shady and breezy. Trees are selected to offer high-quality summer browse (mulberry and willow). Pasture understory forage is warm-season grasses and summer-active legumes (alfalfa and annual lespedeza).*

BOTTOM RIGHT: **Spring and fall pasture area.** *Trees are evenly dispersed, so shade is evenly dispersed. Trees are selected to include species that drop edible fruit in fall (such as apples and pears), or have palatable leaves that drop in fall. Pasture forage is shade-tolerant grasses (like orchardgrass or Virginia wildrye) and legumes (red clover, white clover).*

WARM-SEASON GRASS PASTURE

This is an understory composed mainly of my favorite warm-season native grass (eastern gamagrass), along with alfalfa (lucerne), chicory, plantain, Maximillian sunflower, Korean lespedeza, crabgrass, and a host of other native warm-season grasses, wildflowers, and legumes. The overstory is willows and mulberries. The grasses provide summer grazing for the livestock, with the high-protein willows providing browse and picking up the slack in late summer as the grasses decline in productivity.

The trees are in lines that run in a north-south orientation, so that the prevailing summer wind blows right through and between them. In the morning, animals can be in the shade on the west side of the tree lines as well as in the wind; in the afternoon, they can be in the shade on the east side of a tree line and also in the wind.

The mulberries provide summer fruit for pigs and excellent browse for beef animals. Other summer fruits, such as gooseberries, currants, goumi, Lodi apples, apricots, and wild plums, can extend the fruit drop for the pigs.

WINTER PASTURE

A pasture designed for winter use is composed of friendly endophyte tall fescue, red clover, bird's-foot trefoil, and small burnet, all of which retain their quality well into the winter months. This pasture has lines of pines that run in an east-west orientation, to block the cold north wind in the winter. Underneath the pines are winter-hardy bamboo varieties, which are not only quite shade tolerant, they also retain their leaves and are highly palatable to livestock in winter. Shrubs that retain their leaves in winter, like four-wing saltbush, could also be incorporated into the tree lines.

Between the rows of pines are widely spaced, thornless honey locust trees. These drop high-sugar pods that persist on the ground with minimal deterioration in the winter, providing a high-energy supplement for wintering cattle.

The honey locust pods also contain high-protein seeds with a rock-hard seed coat that makes them indigestible by cattle. The bovine digestive system, however, softens the seed coat enough that it takes in water and swells enough to break. Come spring, the area is used as pig pasture. The pigs sort through the manure and eat the honey locust seeds, which are now digestible because they've been softened.

Blocks of pines stand in the southeast corner of each paddock to provide animals with emergency shelter from blizzards.

SPRING-FALL PASTURE

A pasture for spring and fall has a blend of cool-season grasses, forbs, and legumes, such as low-alkaloid reed canarygrass,

meadow brome, orchardgrass, smooth brome, alfalfa, red clover, white clover, bird's-foot trefoil, chicory, and plantain. The tree overstory might be a diverse blend of oaks for high-carbohydrate acorns and chestnuts for high-carb nuts as well as hazelnuts, walnuts, and pecans for high protein. Additional trees might include autumn olive, apples, pears, and persimmons for high-energy fruits.

This field can be pastured primarily in spring and fall, with an abundance of pig food in the fall and with fruits also relished by cattle or other ruminants. The deciduous trees drop leaves in the fall, which add to the cattle feed supply.

THE FULL PICTURE

Among the three pasture types, nearly year-round grazing is provided for cattle, even during heavy snow cover, and there are fruits and nuts that drop for a good portion of the year to feed pigs (or poultry). No diesel, no fertilizer, no work, except the work happily done by cows and pigs; the whole farm runs on sunshine, and every year the soil gets better.

If it is not already apparent, silvopasture is my hands-down favorite land use. I hope that I have sufficiently explained all the reasons I feel this way, and that you will now share my enthusiasm.

CHAPTER 12 SUMMARY

- Agroforestry is the growing of herbaceous crops and trees together on the same land unit; this combination can offer many advantages, both economic and environmental.
- Agroforestry practices can be classified under the following groups: riparian buffers, windbreaks, alley cropping, forest farming, and silvopasture.
- Riparian buffers are plantings of woody vegetation next to rivers and streams to prevent soil erosion from the watercourse; they can also be designed to produce a harvestable crop, such as timber, fruits, or nuts.
- Windbreaks are used to modify the microclimate of an area. Reducing wind velocity can reduce winter stress on livestock, evaporation of soil moisture on cropland, and wind erosion and sand blasting of seedling crops, and can also be designed to produce harvestable crops, such as fence posts.
- Alley cropping is the planting of herbaceous crops between rows of trees. This is a practice that is especially useful while trees are small and developing, to have cash flow from the land with annual crops between the tree rows.
- Silvopasture is the integration of trees and pasture. It is perhaps the agricultural system with the most promise of carbon sequestration and the most promise of feeding

monogastric livestock (pigs, poultry) from a perennial landscape rather than using grain grown from annual crops in monocultures.

PART IV

Once and Future Farming

Not all forms of agriculture throughout history were destructive to soil, although the one that was—annual grain crops based on tillage—is the one that came to dominate. Our current farming methods too often result from a desire to subdue nature, enabled by diesel fuel–guzzling machines and toxic chemicals to kill any portion of it we deem undesirable.

Perhaps because our ancestors lacked these means, they had to find methods to produce food that involved a partnership with nature. All over the world, Indigenous ancient farmers developed agriculture systems that were remarkably clever, some so clever that they can make us modern farmers feel stupid in comparison.

Since our current farming methods are putting us on what looks like a collision course with disaster, an examination of some of the more innovative ancient systems might aid us in developing the systems of the future. There are also some modern visions of agriculture that use nature as a pattern, rather than a problem, and may offer a wiser path going forward than the one we seem to be on.

This chapter offers a glimpse at these systems, both ancient and modern.

13

Better Agriculture Systems of the Past, Present, and Future

How should we produce food in the future? It is difficult even to guess at a future path without looking at what we have done in the past, and what the consequences of those practices have been.

> *"Those who fail to learn from history are doomed to repeat it."*
>
> *—Winston Churchill, paraphrasing George Santayana*

7,000 Years of Tillage

Seven thousand years ago, an agricultural system developed in the Middle East that was based on growing annual crops (primarily wheat) with tillage. This method of farming spread rapidly from its place of origin because it produced large amounts of food per unit of land area, an obviously appealing attribute. Cultivating shallow-rooted annual crops with tillage had an insidious and disastrous downside, however: It caused soil degradation.

Nevertheless, tillage-based culture of annual crops spread across Europe and Asia. It soon became the dominant method of agriculture because human nature then, as now, placed a higher value on short-term abundance than long-term viability. We may never know what agricultural systems existed all across Europe and Asia (the "Old World") before

being displaced by wheat and tillage, since many of these events took place prior to recorded history.

Meanwhile, during this 7,000-year (or so) period of soil degradation in the Old World, the New World of North and South America was covered in forests and grasslands. Huge roaming herds of bison grazed the grasslands of North America and moved on, allowing the grass to rest and restore vigor between grazing episodes. The people of the grasslands based much of their way of life on harvesting the bison as their main source of sustenance.

The people of the forests harvested and promoted fruit- and nut-bearing trees and shrubs and hunted the deer and other animals that lived in the forests. Only in small clearings were annual plants like maize, beans, and squash grown, mostly as a source of food that could be stored and used during the lean times of winter. These clearings were also moved around from year to year, so the perennial vegetation could recover.

This perennial vegetation of prairie and forest built deep topsoils high in organic matter, particularly the grasslands.

When European colonists conquered the New World, they imposed their agricultural system on the new lands, eliminating many Indigenous practices that were incredibly clever. Fortunately, many of these New World Indigenous practices *were* recorded, and their wisdom is finally being recognized, as we face the fact that our current system of agriculture is not sustainable.

How we farm in the future will have to be very different from how we farm now. While ancient agricultural systems usually lack the productivity required of agriculture today,

their ability to grow food in a way that is more in harmony with nature may offer us lessons for developing new farming methods. These methods, when combined with modern technology, just may produce the agriculture that this planet and the human race desperately needs: one that is highly productive but makes the soil and environment on which it depends better every year, not worse.

How we farm in the future will have to be very different from how we farm now.

Ancient Agriculture that Worked

Following is a sampling of some of those innovative systems that have been largely lost to history, as well as some modern systems that live up to the ideals of high productivity without environmental destruction.

Indigenous American Raised Beds

All over the Americas, Indigenous peoples have used the very interesting and useful agricultural system similar to what we now know as raised beds, but with an integrated system of rain-catching basins in between the beds. (See Figure 15.1.) Resistant to both droughts and excess water, land shaped in

this manner will not only capture all the rainfall on a field and hold it for future use but also keep crop roots in well-drained soils.

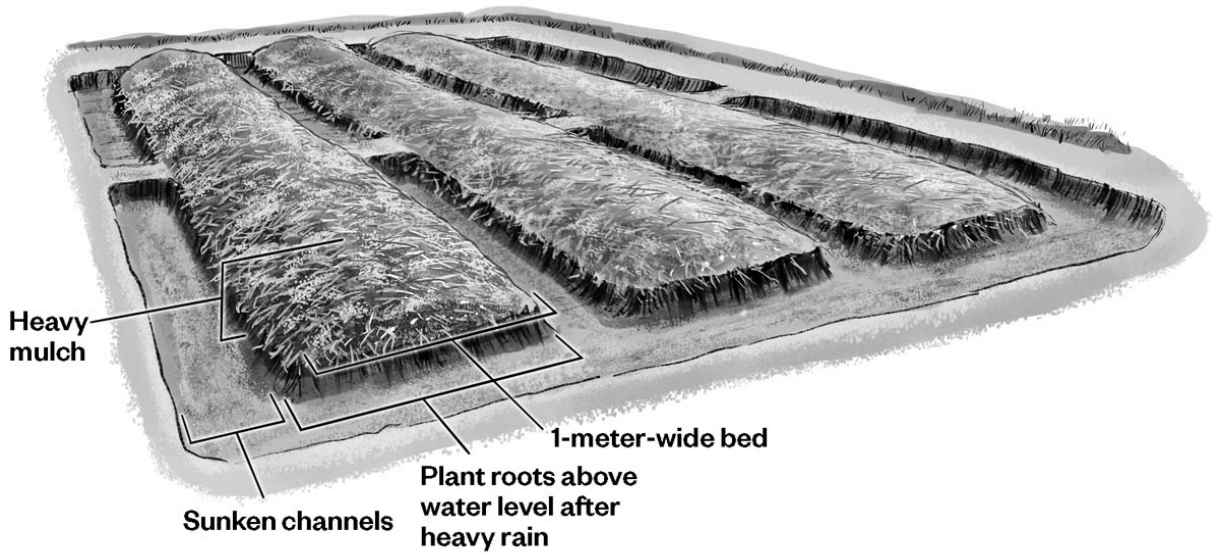
Despite its productivity, this practice was almost entirely displaced by the European farming systems of tilled soil farmed “on the flat” and became largely forgotten. Archaeologists have discovered remnants of this farming system, and in the 2007 Climate Assessment the Intergovernmental Panel on Climate Change recommended it as a method of food production that is resilient to extremes of precipitation. This practice is being revived on a global scale.

HOW DOES IT WORK?

The raised beds are 1 meter wide, with sunken channels in between to hold water and prevent it from running off after rainfall. Ridges, placed every meter or so within the channels, keep the water where it falls. The tops of the beds are heavily mulched to hold moisture and encourage soil biology. The raised beds allow plant roots to be above the water level after heavy rain, and the large amount of surface area exposed to the air allows thorough oxygenation of the root zone.

Recent trials have shown this system capable of producing excellent yields even during extreme drought. The raised beds are also a natural for perennial crops. In this system, both soil fertility and productivity are excellent.

Indigenous Raised Beds

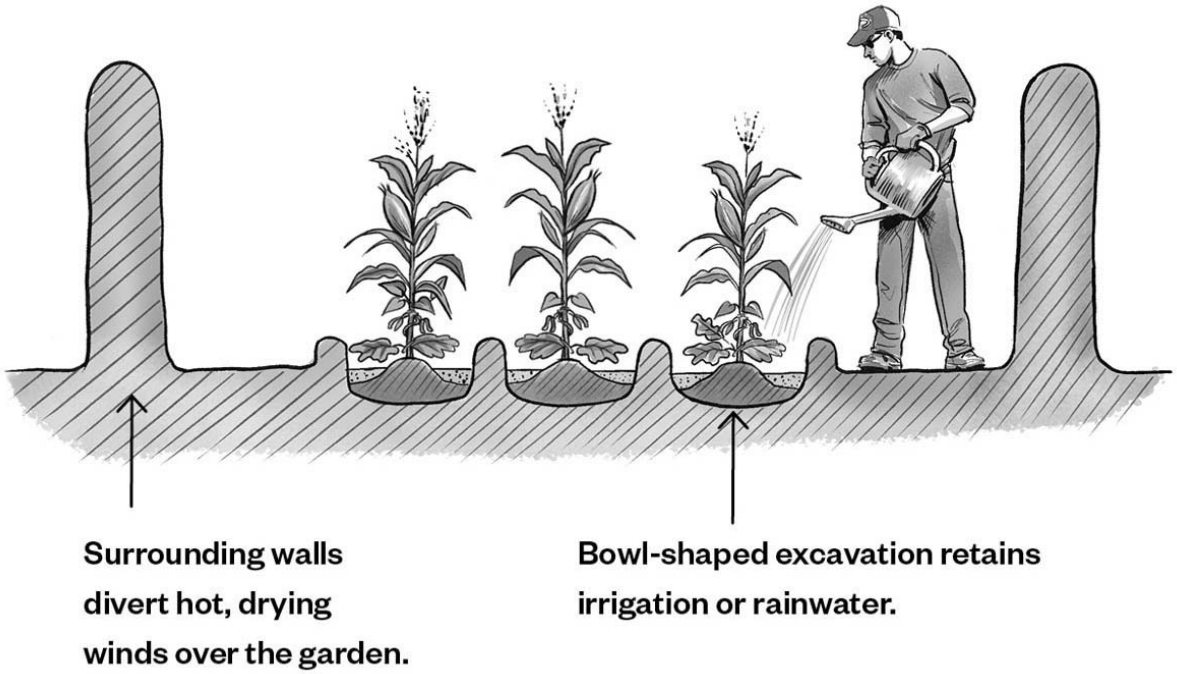


Waffle Gardens of the Zuni

The Zuni tribe of the southwestern deserts (what would become Arizona and New Mexico) have had one overriding concern in producing crops: lack of rainfall. Though infrequent, rain can be intensive in this region when it does fall. Much of the rainfall runs off because the soil surface lacks the cover of living or dead vegetation. The soil gets “capped” or sealed off with a soil layer (often called a desert crust) that retards infiltration of rainwater.

To combat this problem, the Zuni created a different form of planting beds from that used by tribes in more humid areas, one that resembles the surface of a waffle.

Zuni Waffle Garden



HOW DOES IT WORK?

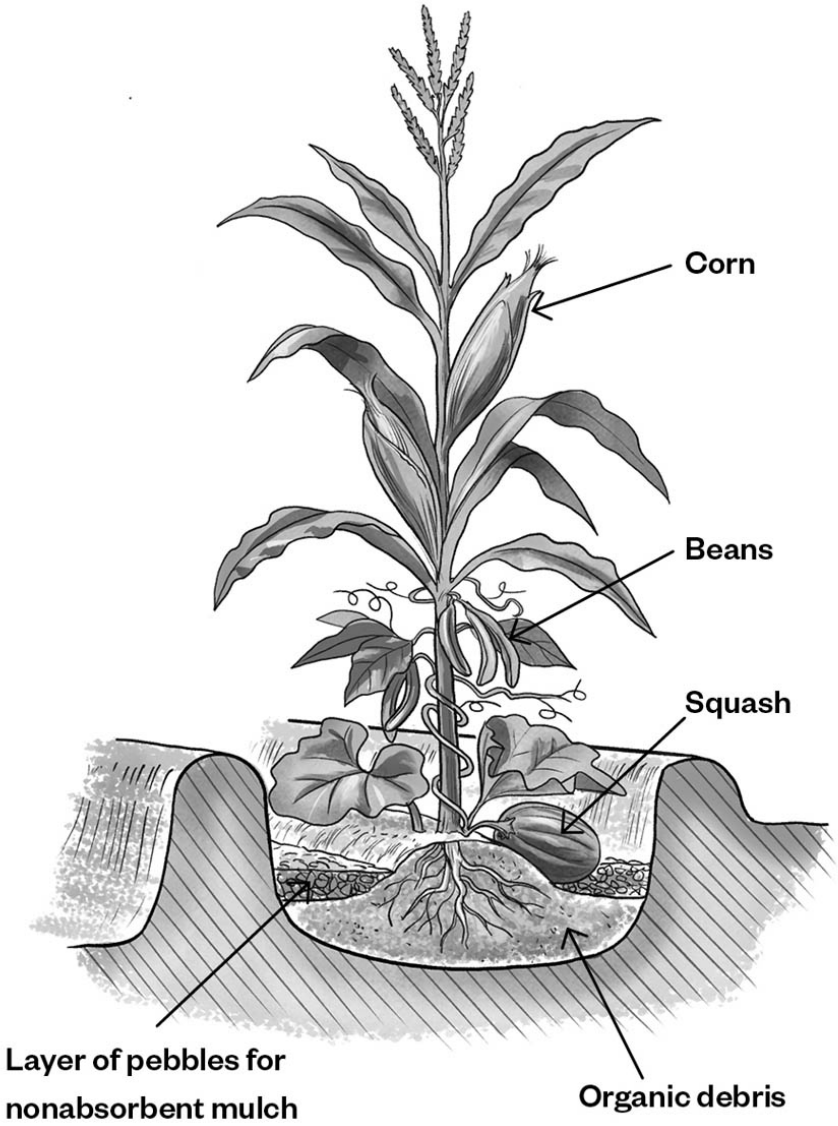
The crops are grown in little sunken pockets that help retain moisture and position the newly emerging crops out of the direct path of the hot, drying winds common to the region. The farmer plants the crop into a small elevated mound within the pocket, mulches the area around it, and places a loose stack of rounded stones over the mulch.

Any rain, even small amounts, will run off the rocks and into the mulch below. The rocks keep the sun and wind from evaporating moisture from the mulch or the soil below.

Three Sisters Polyculture

Indigenous American farming cultures centered around a polyculture known in many tribes as the “Three Sisters,” consisting of corn, beans, and squash. These crops are highly synergistic and complementary.

Three Sisters



HOW DOES IT WORK?

The corn grows the tallest of all the plants and, due to its highly efficient C_4 photosynthesis, provides the bulk of the yield. It also serves as a trellis for the climbing beans, which in turn provide biologically fixed nitrogen to the soil for the other crops, and their seeds supply the farmers with dietary protein. Squash offers a weed-smothering mulch, and the prickly hairs on the squash leaves repel deer. The squash fruit are rich sources of many vitamins, particularly beta carotene.

Monocrop corn is often considered the single most efficient calorie-producing crop per area. Research by Dr. Jane Mt. Pleasant, however, indicates that the corn-bean-squash polyculture can produce 20 percent more calories per acre than monocrop corn and 50 percent more protein. Currently, the Three Sisters method of gardening is mostly a botanical curiosity practiced only by home gardeners and school groups. But could this polyculture, so successful in the past, be adapted for use in the future?

Polyculture on the Livestock Menu

The roadblock to planting polycultures in modern times has been that you can't harvest a polyculture with a grain combine, as you would in a monoculture. But what if it were not harvested with a combine? What if it were harvested with livestock instead, using modern movable electric fence to ration it out slowly, one day's feed at a time, to limit trampling and waste?

A current feedlot ration for a fattening steer might consist of:

- about 80 percent corn (for bulk starch)
- 10 percent corn silage (as an appetite-stimulating wet feed)
- 5 percent protein meal (often soybean meal or another oilseed meal)
- 5 percent alfalfa hay (as a roughage source and source of vitamins found in green leafy material)

Interestingly, a Three Sisters polyculture will usually yield on a per-acre basis (as a percentage of total dry matter yield):

- about 80 percent corn grain
- about 10 percent squash fruit (nutritionally equivalent to corn silage, with seeds that contain a chemical compound that helps eliminate intestinal parasites of livestock)
- 10 percent beans, equivalent to the oilseed meal in the feedlot ration

Toss in a winter annual cover crop for a high-protein green roughage, along with the corn residue, and you have a well-balanced feedlot ration.

And the same crops can just as easily be harvested with swine, or even with poultry aided by a rotary mower to help them access the grain and internal contents of the squash. No need for mechanical harvest, transportation, drying, or grinding and mixing the feed; no need for feed trucks to deliver the feed, no need to gather and haul manure back out to the fields.

The animals get a fresh, clean “feedbunk” to eat from every day, rather than a mouthful of mucus lying on the bottom of the trough left there by their penmate that has a respiratory disease. The manure from the animals is deposited right where it will benefit the next crop to follow on the field.

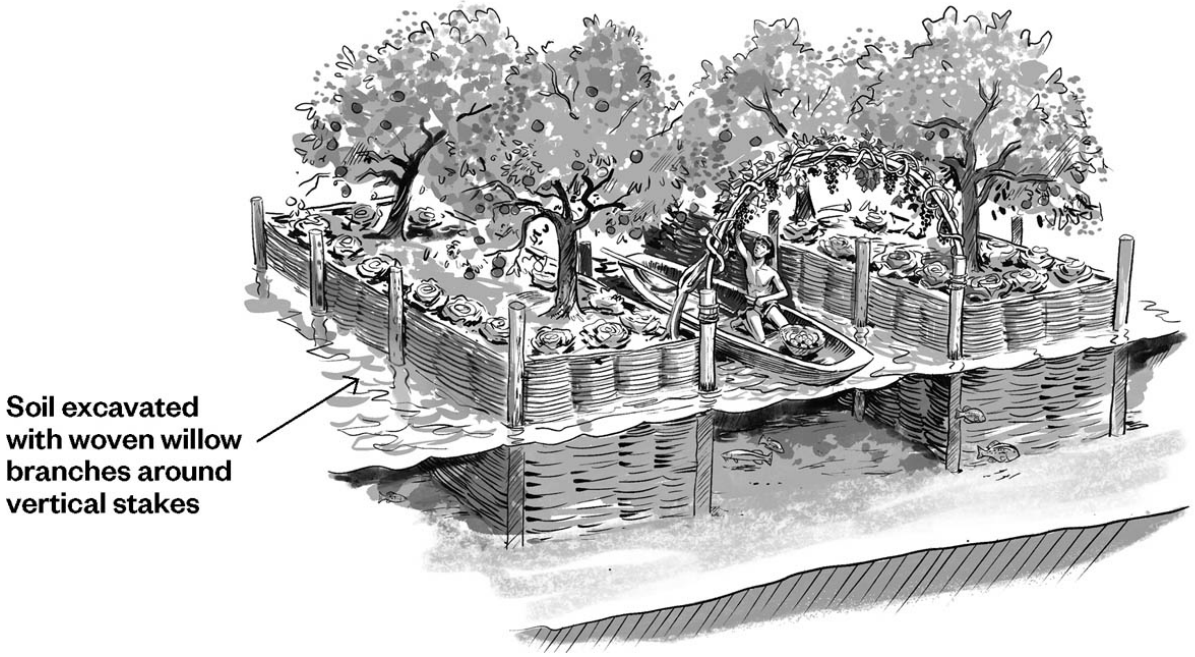
If we are to continue feeding animals the products of annual plants like corn, does this not seem like the most environmentally sound way to do so?

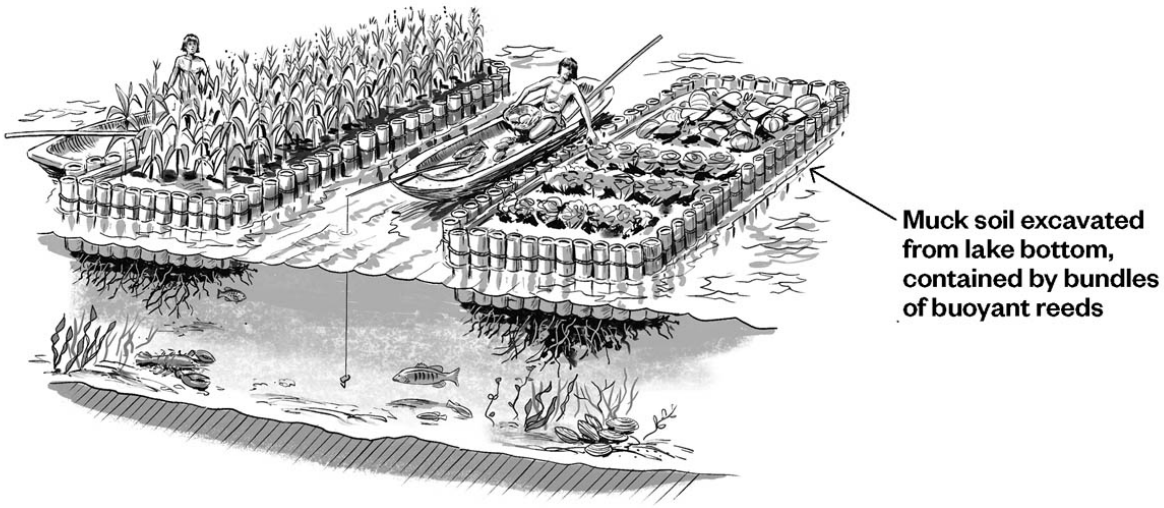
Chinampas in Mexico

In modern times, we think of farming as a practice we do on land. In ancient times, in flood-prone areas around the world, many people also farmed on water. One amazing innovation, almost lost to the modern world, was is the creation of farmland out of wetlands without draining them.

Mostly gone, chinampas were an ingenious method of intensive agriculture practiced by ancient civilizations in swampy areas of Mexico. Farmers created raised beds in lakes

by weaving tight fences of willow limbs into a rectangular shape, then filling the interior with mud dredged from the lake bed. They also constructed floating beds from bundles of hollow, buoyant reeds, so that floods would not wipe out the crop; the beds simply floated up with the rising water.





HOW DID IT WORK?

The farmers created canals between the beds to allow for easy transport of the food by canoe. Sometimes they constructed arched trellises over the canals and planted vine crops on them so that someone sitting in a canoe could pick the fruit. They could raise fish, crayfish, and mussels in the canals, and the narrow width of the canals allowed easy harvest with nets. The water also attracted large numbers of ducks that controlled many insect pests and provided an additional food source in meat and eggs.

The beds were fertilized not only with the lake sediment but also with human wastes that were recycled back to the beds. Although it took a tremendous amount of labor to create these beds initially, once in place they provided a great deal of food per unit area and per effort expended.

Unfortunately, the amazing chinampas system was destroyed by the conquering Spaniards.

Floating Villages of the Uros on Lake Titicaca

A few thousand miles south of the chinampas in Mexico, another civilization independently developed a very similar form of agriculture. The Uros people live directly on Lake Titicaca in the Andes Mountains on the border between Bolivia and Peru, 3,812 meters (12,506 feet) above sea level. They build gardens and houses on floating platforms made of totora reeds. (See Figure 16.2.)

HOW DOES IT WORK?

Entire villages sit atop these platforms, which have small openings for fishing. The builders cut the totora reed root mass into blocks, which form the foundation for the platforms, and cover them with bundles of reeds laid horizontally, staked, and lashed together. The reeds grow on the beds, and the top layers are renewed as the underlying layers decay. The totora reed roots can also be mashed into a starchy flour as a foodstuff!

The farmers also dredge up muck from the bottom of the lake and place it on top of the reeds. That becomes a layer of soil where they can grow potatoes and quinoa.

Other primary sources of food include fish and waterfowl. The floating islands create an excellent fish habitat, since the decaying bottom layer of the reed beds nourishes algae and plankton, which form the basis of an aquatic food chain.

Al Tahla Floating Islands of the Ma'dan in Iraq

On the other side of the planet, in a far different environment, are the Al Tahla floating islands of the Ma'dan (often called the Marsh Arabs) in Iraq, at the junction of the Tigris and Euphrates Rivers. At one time, as many as a half-million Marsh Arabs lived in this huge wetland, the biggest in Asia.

HOW DOES IT WORK?

The floating islands of the Marsh Arabs are constructed of a reed called *qasab*, which can also be used as food for water buffalo and as a starch source for humans. Alternating layers of reed bundles and mud, dredged from the marsh bottom, form a floating island on which both houses and gardens are built. (See Figure 16.3.) Houses, called *mudhifs*, are also constructed of reeds.

Unfortunately, because the Marsh Arabs were Shia Muslims, they were persecuted by the government of Saddam Hussein, which built large projects intended to drain the wetlands. The Marsh Arabs were forced to flee, and although the Hussein regime was toppled and the drainage stopped, most of the Marsh Arabs have not returned. Only about half of the original wetland area has been restored, and only about 10,000 of the Marsh Arabs remain. The loss of this beautiful and unique civilization is a terrible shame.

Floating Gardens of Myanmar

Yet another floating garden system is found on Inle Lake in Myanmar (formerly known as Burma).

These 1-meter-thick (3.2 feet) floating beds are made of water hyacinth, seagrass, and bamboo overlaid with mud dredged from the lake bottom. On top of the floating beds the main crop is tomato, along with beans, cucumbers, squash, onions, and eggplants.

Stone Terrace Farming in the Andes

Most farmers would love to have nice, flat fields full of deep, dark, fertile soil in an area that receives frequent rain. Unfortunately, only a few places on the planet fit this description. Most of the world is too dry, too rocky, too shallow, too salty, too something to farm as we would like.

One of these "somethings" is land that is too steep and sloping. Many ancient agricultural societies, however, developed methods—all around the world, independently of one another—to farm on some of the steepest slopes in the world. Today these ancient sites, some of which are still in use, are true marvels of human achievement and among the most beautiful places in the world.

Ollantaytambo is a village in the Peruvian Andes with slopes as steep as 70 percent. A person familiar with modern agriculture would believe that this terrain has absolutely zero potential for farming. Who could farm such steep rocky slopes? Why, your tractors would tip over! The ancient Peruvians who populated this area (there is evidence that the original inhabitants who built these structures predated the

Incas) apparently felt otherwise and created a marvel of engineering that made agriculture not only possible but even incredibly productive.

HOW DOES IT WORK?

These farmers constructed stone walls by hand and filled them with imported soil, creating terraces that provided level surfaces for growing crops. The soil appears to have originated largely from areas outside the valley, and historians believe humans or animals carried it in baskets on their backs, since wheeled carts were unknown to this area prior to European settlement.

The valley sides also have channels cut in them. These divert rainwater through an elaborate series of irrigation ditches, in which one terrace is watered and any excess water from that terrace runs into a spout and drops to the terrace below. The spouts can double as a cooling, cleansing outdoor shower for workers on the terraces.

Other stone terraces incorporated stone buildings for food storage into their structures. On these terraces the Peruvians cultivated over 70 species of crops, including potatoes, tomatoes, cotton, quinoa, and maize. For each of these crop species there was also a wide range of varieties with unique characteristics and flavors.

Rice Terrace Farms

It is no secret that the most popular food crop in Asia is rice, which is grown in paddies. The system of growing rice in

paddies lends itself exceptionally well to nice flat fields in naturally wet areas. But when human population pressures force people to move into hilly ground, paddy rice ceases to become an option, because a rice paddy needs a nice, perfectly level slope to maintain a uniform water depth. Or does it?

As several civilizations have shown all across Asia, it is possible to grow rice on exceptionally steep land with the construction of rammed earth retaining walls to make a series of level paddies. These paddies are fed by diverting rivers uphill into a series of canals (just as in Ollantaytambo) to fill the paddies in sequence down the slope. In addition to rice, these artificial wetlands also can be used to produce frogs, fish, and shrimp as well as many other aquatic animals, and when drained they can be sown to crops more suited to dry soil as a system of crop rotation, to prevent a buildup of aquatic weeds or rice diseases and pests. Such farms are found in the Philippines, Bali, and China, among other places.

Terrace Farms in the Desert

Terrace farming can also be used to capture and hold water on sloping soils in desert regions. Examples of stone-terraced farms can be found around the village of Jabal al-Akhdar in Oman, where the terraces capture and retain water that would otherwise run off and use it to grow an abundance of fruits and nuts.

Indigenous Forest Farming

Our modern minds usually think of forests as an impediment to agriculture; after all, they get in the way of our equipment! In North America, European immigrants eagerly hacked away at the forests and cleared and plowed them (all of which required immense effort) to plant annual crops like wheat, just as their ancestors had done in Europe.

Knowledge of the agriculture that existed before that transition in Europe has been mostly lost to history. There is, however, some knowledge of what existed before in other regions more recently cleared from forest: a system in which forest dwellers derived their food from the forest itself.

A Never-Ending Story

It is estimated that the British Isles were at one time over 90 percent forest, populated with typical forest animals such as wolves, bears, and wild boar. When the Romans brought with them the Middle Eastern farming system of tillage and wheat, the forests were cleared and the land plowed, just as they had been in continental Europe before. Now Britain has very little forest cover, only about 13 percent.

CHESTNUT NATION

It is often assumed that the forest encountered by the first European settlers on the Atlantic coast was a wild, pristine

ecosystem unaltered by human hands. Analysis of the fossil pollen record tells a different story. The American chestnut, a food producer of amazing virtue, accounted for only about 5 percent of the pollen prior to the arrival of the first humans to North America. By the time Europeans arrived, chestnuts comprised 50 percent of the pollen. Apparently, Indigenous people planted chestnuts and eliminated the competing trees to chestnut.

HOW DOES IT WORK?

The chestnut was a food staple itself but also provided food for deer, squirrels, and black bear, which in turn became food for humans. After European settlement, the trees provided food for free-ranging pigs. This system produced considerable food per unit area with little human intervention required.

INDIGENOUS TREE FARMING

Chestnut farming holds tremendous promise, since chestnut yields from orchards of mature trees can rival wheat in producing carbohydrates per acre. In addition to the apparent culture of the chestnut, pollen records indicate that the range of black walnuts and pecans expanded by moving upstream over time, indicating that somehow they were carried against the flow of water; it stands to reason that Indigenous people did the carrying and planting. Pecans and walnuts provide nuts that are high in both fat and protein.

There is also evidence that Indigenous people propagated other native fruits such as persimmons, pawpaws, buffalo berry, and chokecherry, either accidentally or intentionally.

Could this long-ignored system, which worked so well with no need for fossil-fuel–powered intervention, be a pattern upon which to base a future agriculture system in the naturally wooded areas of the US?

Or perhaps, as discussed in Chapter 12, the vast acres of corn and soy used to feed pigs in the Corn Belt of the US could be partially replaced with forests of chestnuts, hazelnuts, oaks, pecans, and walnuts to feed those same pigs, who could also graze on an understory of grasses and clovers.

Blight—and Resistance

The arrival of the chestnut blight on an imported foreign species of chestnut tree soon led to the near extinction of this valuable species. The American Chestnut Foundation is working to reestablish this species in a blight-resistant form, and several people are growing hybrids of American chestnuts and Chinese chestnuts.

The hybrids range from ones similar to the American version, a massive tall-growing timber species, to ones more resembling the Chinese chestnut, which is a much smaller version unsuited for timber but with high yields of large nuts.

Dehesa of Spain and Portugal

The dehesa is an area of Spain and also Portugal (where it is called Montado) characterized by a savanna of oak trees and grasses. This area was never converted into traditional cropped agriculture due to the poor soil and relatively arid climate.

HOW DOES IT WORK?

Unlike many other ancient farming systems, the dehesa is still intact and operational. The grasses provide pasture for ruminant livestock, while the acorns that fall from the oak trees provide food for free-ranging Black Iberian pigs. The tannins in the acorns impart a distinctive flavor, which is captured in one delicacy of the region, *jamon iberico de bellota*, which roughly translates into "acorn-fed Iberian ham."

This method of finishing pork does not require the growing of corn or soybeans, or even farming at all. The pig feed simply falls from the trees and provides a bonus crop (in addition to beef and lamb) from the pasture. The trees provide both food and shade for the livestock.

The dehesa is probably not completely natural, having most likely been sculpted over past centuries by human hands. The end result is a stunningly beautiful, idyllic landscape that produces food with minimal input of petroleum-derived products.

Although the dehesa is still present, the economic incentives related to the high prices for jamon iberico de bellota have led to pigs being raised in larger numbers than the natural acorn crop can support. As a result, many pigs are

being fed imported corn or barley in order to bolster their numbers.

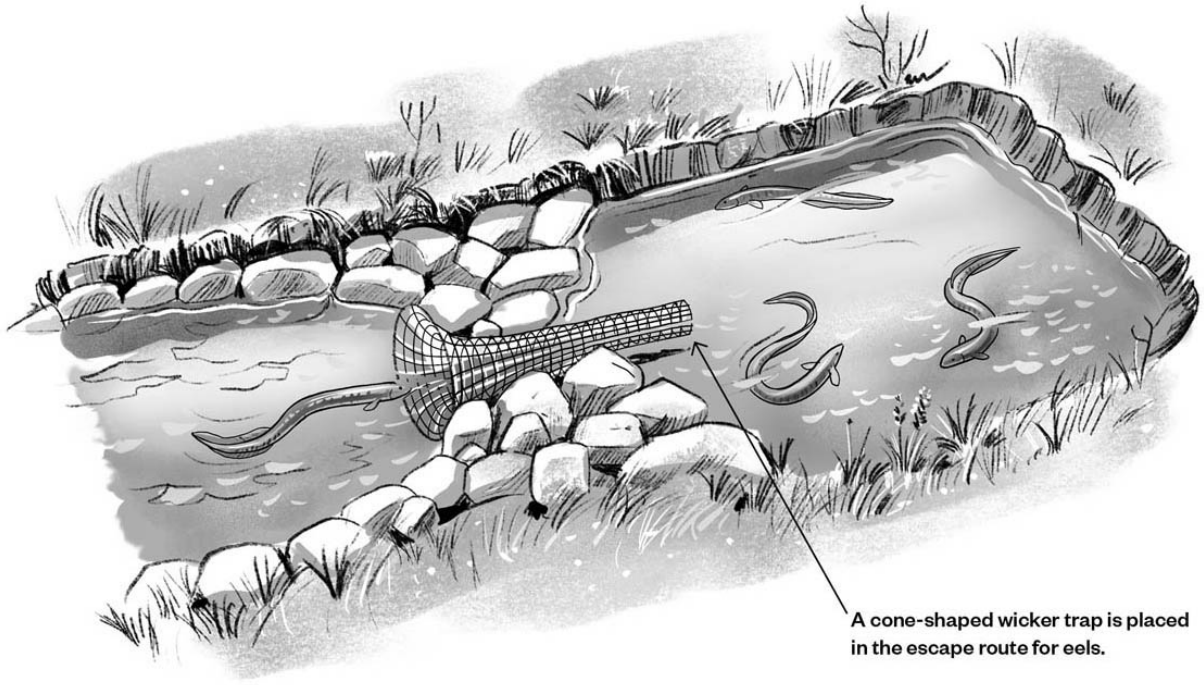
This defeats the whole idea of a system in which pigs harvest food produced without human intervention or fossil fuel inputs. It is still a better system than pigs fed in confinement, though, and the importation of minerals and organic matter in the form of the grain is enriching the otherwise poor soils.

Eel Trapping in Australia

One ancient system of agriculture that was rediscovered relatively recently is the elaborate canals and traps used by the Gunditjmara people of the Budj Bim area in Australia, about 350 kilometers west of Melbourne. These canals and traps have been dated at as much as 8,000 years old, which would make them older than Stonehenge and the Egyptian pyramids, but they have only recently been rediscovered and recognized for their cultural significance.

HOW DOES IT WORK?

Eels, a highly desired food fish, naturally migrate in from the ocean each year, moving up natural rivers and streams, but waterways are sparse in mostly arid Australia. The Indigenous Australians constructed a series of canals to extend the eel migration much farther inland than what naturally occurred, with a series of constrictions placed in the canals. These allowed cone-shaped wicker baskets to be placed at the narrow points to act as fish traps to catch the slippery creatures.



Qanats of Persia

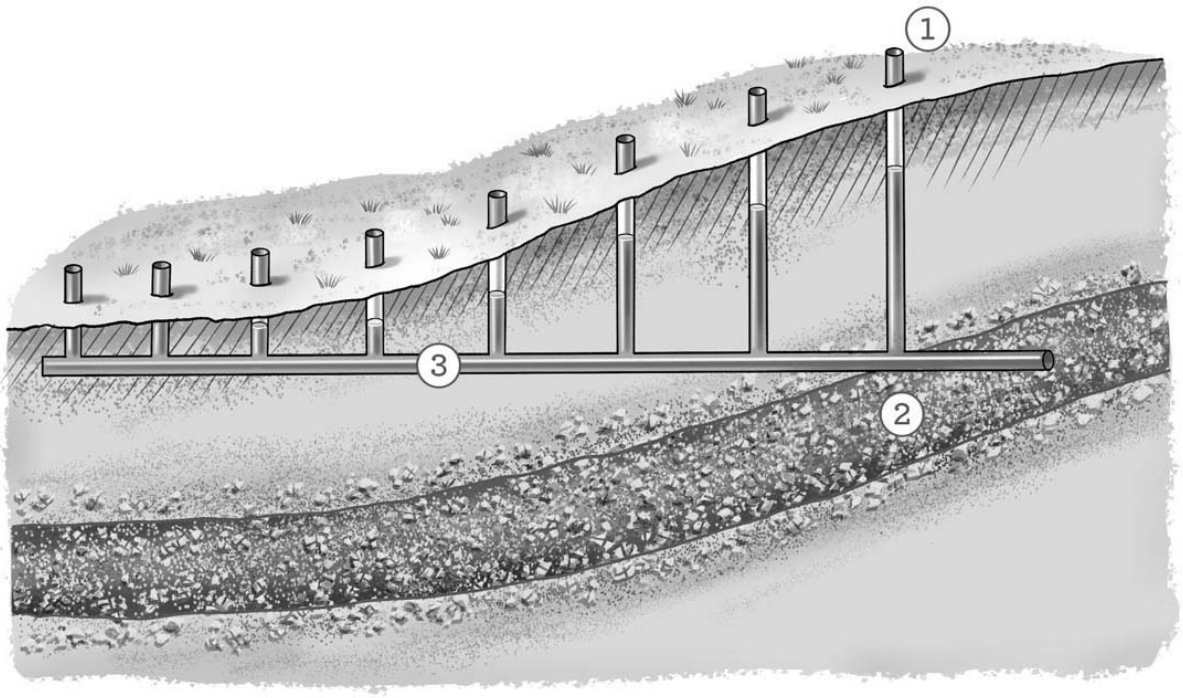
Qanats are a system of underground aqueducts that conducted water all over ancient Persia, and many are still in use today. These structures make it possible to irrigate crops far from the original water source. The elaborate engineering and coordination needed to pull off this feat with hand tools make this truly a marvel.

HOW DOES IT WORK?

The aqueducts operated entirely by gravity and could move water for many miles in the desert with little evaporation loss. The ventilation/access shafts to the surface that were created during construction become access wells to obtain water at

multiple points along the entire length of the qanat (see illustration below).

To take advantage of the cool conditions brought by the underground water, some people built entire underground rooms beside the qanats to escape the brutal desert heat. Likewise, cooling towers were used to draw air through the qanat and pull the cooled air into living spaces.



ABOVE: *Qanats allow easy access to groundwater with hand equipment.*

1. Access shaft /well
2. Groundwater
3. Underground aqueduct

Visions of the Future: Organic No-Till

As much as it infuriates many people to hear it, the invention of glyphosate (Roundup) was an Earth-changing event, and partly for the better; it was key to making no-tillage farming practical and affordable. The original, and still the major, reason for tillage worldwide is to eliminate competing vegetation to the crop to be planted. Glyphosate made it possible to spray a single chemical that killed all weeds, and even the roots, prior to planting, without tillage. We were told that it had no soil residual and that we could plant any crop immediately after spraying with no ill effect. Mounting evidence, however, now tells us it is not quite as benign as we once thought and does in fact have lingering effects.

No-till allows the maintenance of surface mulch, intact root channels, and undisturbed soil biology. Although no-till in its current state is thought to be highly chemical dependent, the total amount of herbicide used is often less than that used in conventional tilled agriculture. That's because most weeds are adapted to bare soil conditions and thrive in tilled soil, so further herbicide applications are needed. Cocklebur, for example, requires soil disturbance to germinate. It eventually disappears in no-till fields because the spiny seedpods hold the seeds away from soil contact, and they do not germinate without tillage to bury the seeds.

My Trajectory

Historically, I have been aligned with the high-chemical no-till system of farming and thought organic farmers just didn't understand science. I had the chemical weed control handbook for Kansas pretty much memorized, and I knew fertilizer use inside and out. I believed no-till to be the way to go, even if it meant more glyphosate use, because with no-till, soil remained in place. With tillage, soil was prone to erosion, and once the soil washed downslope it was impossible to economically move it back up the hill where it was before. With no-till made possible by glyphosate, the soil stayed on top of the hill where it belonged.

One friend of mine, a prominent no-till advocate and former president of No-Till on the Plains, summarized my feelings when I heard him say, "The jury may still be out on the effects of glyphosate, but the jury has been in for 7,000 years on the use of tillage, and the jury has returned a guilty verdict. Tillage has been found guilty of ruining every civilization that has used it to produce food. It has left devastation in its path."

ALARM BELL GOES OFF

Then I heard some of my friends talking about the work of Dr. Don Huber, who was sounding alarms about the dangers of glyphosate. This was not some old chemophobic Luddite. This was a respected scientist in the agriculture department of a major land grant university, and his evidence was compelling. I began to question the wisdom of using glyphosate. Ironically, at the same time, many of my organic farming friends were

becoming increasingly concerned about their use of tillage; they had seen the positives that no-till had brought their neighbors, although they were not going to give up and start using synthetic chemicals.

I have many friends who are devout no-till advocates, and others who are devout organic farmers. Historically, these two groups have held 180-degree different views on the "right way" to farm, but this is changing. A decade ago, no-till educational events focused on the latest chemistry and machinery; now they focus on cover crops and soil biology. No-till farmers are often pictured as spray-happy nozzle heads, but no one who is trying to make a profit relishes the thought of paying for an unnecessary spray trip.

THOUGHT CONVERGENCE

Today, in no-till educational events, there is more focus on controlling weeds through an understanding of biology in order to prevent weeds, insects, and diseases from becoming problems in the first place, instead of expensive chemical rescue treatments. Likewise, organic farmers are now coming to realize how destructive tillage is and are trying to learn to control weeds without tillage—and organic farming events are now focusing on how to reduce tillage in their operations.

Now we are seeing is a convergence of thought between no-till farmers and organic farmers, two groups that often choose their farming method out of concern for the environment. I have frequently said that I can't fault a person who is doing what they believe is right, even if I disagree with *what* they believe is right.

Now a few scientists and farmers are exploring methods to combine the ideas of no-till and organic farming. Prominent among them are Jeff Moyer of the Rodale Institute and Randy Anderson of the USDA in South Dakota. The concept of "organic no-till" has become the holy grail of agriculture. Innovations that make organic no-till practical—such as using cover crops for fertility management and weed control, and roller-crimping cover crops instead of terminating them with herbicides or tillage—have become increasingly common.

Even if a person is not interested in farming completely organically, the prospect of eliminating much of the cost for fertilizers and weed control has to be exciting. The lessons learned from "organic no-tillers" can be quite valuable to everyone in agriculture.

Organic Farming Challenges . . .

There are two primary difficulties in organic farming. One is providing soil mineral fertility (methods for accomplishing this are described in Chapter 6). The other is controlling weeds, which are far more challenging to overcome in an economical manner.

Of course, weeds can be controlled by hand pulling or hoeing, but the amount of land a person could operate in such a manner would be quite limited. Tillage is often used for preplant weed control in organic farming, but at the same time it encourages another crop of weeds to sprout, which must be controlled by other means after emergence. There are tillage

tools that can be used after crop emergence, such as row crop cultivators, but all tillage tools result in soil degradation.

If we are to restore soil, we must find a means to farm without tillage, whether organic or not. Controlling weeds without tillage is without question the single biggest challenge in organic farming.

. . . And Solutions

One of the most promising ways to make organic no-till a reality is weed control via a thick mulch created by a terminated cover crop. This can be accomplished by planting a cover crop, then terminating it by nonchemical means, such as with a roller-crimper (see Figure 7.3) or by using a cover crop mixture that winterkills in temperate climates. The thick mulch prevents small seeded weeds from reaching sunlight before the seedling runs out of stored energy contained in the seed. Another no-till, nonchemical weed control strategy is to use cover crops to make nitrogen unavailable to weeds.

An Organic No-Till Pioneer

JERRY LAHNERS, Hebron, Nebraska

One of the pioneering organic no-till farms in my area is JNG, LLC, operated by Jerry Lahners of Hebron, Nebraska. Jerry has found a system that is capable of providing both weed control and nitrogen fertility with one practice: roller-crimped cover crops.

He farms in mostly a corn-soybean rotation under center-pivot irrigation, although he also raises crops of winter wheat and spring peas. Jerry uses a cover crop of rye drilled after corn harvest (or aerial seeded prior to harvest into standing mature corn) to soak up excess nitrogen left after a crop of corn; then he uses a roller-crimper to terminate the rye stand after it begins to shed pollen and no-till drills right into the mat of rye residue.

Meeting Nitrogen Needs

The growing rye soaks up all the leftover nitrogen, creating a low-nitrogen condition in which weeds are starved for nitrogen, but the nitrogen-fixing soybeans don't mind. The flattened rye mulch also is a barrier to sunlight for weed seedlings, through which they must grow to reach sunlight.

Currently, Jerry is also drilling the rye in and waiting until after the soybeans emerge to begin roller-crimping. He feels that the extra couple of weeks allows the rye to be more competitive with weeds and to pump extra root exudates into the soil benefit the soil biology.

Once the soybeans reach leaf-yellowing stage, a helicopter is hired to spread hairy vetch seed over the top of the beans. In the spring, the vetch is allowed to reach bloom, and then it is roller-crimped with the corn planted at the same time. The vetch mulch provides both weed control and slow-release nitrogen. Even though vetch is a legume and makes nitrogen, at termination time, all the nitrogen is in the form of protein, not in a form available to weeds.

A low rate of a readily available organic fertilizer, such as fish hydrolysate, can be put right next to the row to provide nitrogen to the corn plants until the vetch begins to break down and release nitrogen to the corn. This temporary period after planting—in which nitrogen is available to the corn but unavailable to the weeds—allows the corn to get a head start and canopy over the weeds, so even if they do eventually emerge through the vetch mulch, they don't compete well with the much larger and better-established corn plants.

Most of the nitrogen needs of the corn are also met by the vetch. Jerry is quick to point out that this would not be the case if he were just beginning to get into cover crops; in the early stages of using cover crops in an organic system, he supplemented the crop nitrogen needs with poultry litter. But after a few years of using cover crops,

the pool of mineralizable organic nitrogen builds up and provides a higher and higher amount of nitrogen each year it is needed.

Ideas for All

Jerry believes that there are ideas here for every farmer. Organic farmers can see that tillage is *not* necessary for organic farming, and there are other means to control weeds. Also, he says, there is no reason at all that conventional farmers (meaning farmers who are not certified organic) couldn't use these same methods to reduce their costs of fertilizer and herbicide, by applying those synthetic inputs only if the cover crop system is inadequate. He also feels we are just scratching the surface of what can be accomplished in improving the environmental footprint *and* the economics of farming, whether certified organic or not.

Organic "Weed & Feed"

In organic farming, cover crops are the new "weed and feed." In my job as an agronomist with Green Cover Seed, I advise a number of organic farmers on using cover crops in a rotation to provide both weed control and nitrogen fertility.

HOW DOES IT WORK?

The following Corn Belt organic farming no-till crop rotation is a strategy used by several of my customers with considerable success.

- **Spring of Year 1:** Corn, planted into roller-crimped cover crop based on hairy vetch and balansa clover
- **Fall of Year 1:** Drill (or aerial seed) rye-based cover crop into corn around time of harvest
- **Spring of Year 2:** Plant soybeans into roller-crimped rye cover crop
- **Fall of Year 2:** Drill wheat into soybean stubble immediately after soybean harvest
- **Summer of Year 3:** Drill summer-grazing cover crop immediately after wheat harvest (sorghum-sudan, pearl millet, sunflower, cowpeas, sunn hemp, with a high percentage of legumes)
- **Fall of Year 3:** Graze off summer-grazing mix in late August or early September, then roller-crimp after grazing, and drill in a blend of brassicas, spring peas, oats, balansa clover, and hairy vetch

The roller-crimping in the fall of Year 3, if done by late August, will kill summer annual broadleaf weeds like water hemp and Palmer amaranth. All the winter mix except hairy vetch and balansa clover will winterkill, leaving a composition in the spring that is highly legume dominated and provides a high level of nitrogen for the corn. Including a small amount of an overwintering cereal grain like wheat will help maintain

desirable soil structure, but often enough volunteer wheat will be present in the mix to provide this effect.

Permaculture

In the 1970s a Tasmanian farmer named Bill Mollison wrote a book called *Permaculture: A Designers' Manual*, describing a method of living based on the mimicry of natural systems and patterns. Much of permaculture is based on the planting of **guilds**, or groups of plants that coexist well due to complementary attributes, such as leguminous shrubs associated with nut trees, and pollinator-attracting flowers underneath fruit trees that require insect pollination.

HOW DOES IT WORK?

Permaculture is not just a system of agriculture but rather a complete way of living designed to the environment. There are permaculture systems suited to humid tropics, hot deserts, temperate areas, and most likely every other region on the planet. Now a worldwide phenomenon, permaculture has practitioners around the globe, although the amount of total land area involved in permaculture systems is still minute compared to that of large-scale conventional agriculture.

In many respects, permaculture is the perfect system for soil improvement and stewardship: It relies on intelligently designed polycultures of perennial plants with little or no tillage in the system. In that way, it offers much of the same

soil benefit as a natural forest or prairie, but with far more food production potential.

Permaculture Design

This method allows practitioners to live “light on the land” with an agriculture and lifestyle that are part of nature, rather than a domination of nature. In a successful permaculture design the system will:

- capture and store sunlight
- produce no waste
- be self-regulating and self-adjusting
- produce multiple products
- incorporate diversity
- be based primarily on perennial plants
- maximize the edge effect between two or more vegetation types
- mimic natural patterns.

PERMACULTURE ZONES

A permaculture farm is set up in five zones.

Zone 0 is the house. It typically has a number of ecofriendly features such as passive solar design, rainwater harvesting for potable water, and gray water used for irrigation of nonedible plants. The house itself is built out of locally available

materials (stone, locally milled lumber, straw bales, rammed earth, etc.) and built to fit in the environment (shading and passive cooling systems for hot regions, a strong sloping roof for high rainfall, thick insulation for cold environments, etc.).

Zone 1 is the area immediately surrounding the house and features plants and components that would be visited often, such as plantings of salad greens, cold frames or greenhouses, compost piles for kitchen waste, and laying hens for ease of gathering eggs daily. Annual plantings would also be located in zone 1. The idea is to locate high-labor or frequent-use areas close to the house to minimize unnecessary traffic.

Zone 2 is primarily perennial crops that need less maintenance, such as fruit trees and perennial vegetables such as asparagus.

Zone 3 contains more extensive, low-maintenance plantings that may be harvested only once annually.

Zone 4 is a pasture or timber area that need not be visited often.

Zone 5 is for wildlife and natural ecosystems.

PERMACULTURE PLANTINGS

Permaculture plantings are carefully thought out, with each plant serving a purpose, and often multiple purposes. These associations of plants are called guilds, and they include multiple layers designed to maximize sunlight capture.

The topmost layer, the canopy layer, is composed of tall trees such as oaks or black walnut. The understory layer is composed of smaller trees, such as pawpaws or persimmons or apples. The shrub layer can often be of fruiting species such as blueberries, gooseberries, or brambles (such as raspberry). Herbaceous plants are ones that do not have woody stems and in temperate areas die back to the ground every year, such as Jerusalem artichoke, wild onions or ramps, or asparagus.

The ground cover layer consists of low-growing plants that cover the soil surface, such as strawberries and white clover. There is also a soil layer, which may have edible products such as truffles or Jerusalem artichoke tubers.

These plants are put into guilds together based on their compatibility (for example, black walnut has a compound in its root exudates and leaves that is toxic to many plants but stimulates black raspberry) and function. Nitrogen-fixing plants are especially desired in a guild.

PERMACULTURE LAYERS

ABOVE:

1. Tall tree layer

5. Ground cover layer

2. Small tree layer
3. Shrub layer
4. Herbaceous layer
6. Root layer
7. Vine layer

For example, white clover is often used as a ground cover because of its ability to fix atmospheric nitrogen into plant-available forms. (See Figure 10.2.) Nitrogen-fixing shrubs, such as goumi or autumn olive (which harbor the nitrogen-fixing actinomycete Frankia on their roots), can provide edible berries as well.

Plants that produce flowers with pollen and nectar are often used to attract beneficial insects, such as lady beetles and lacewings, to eat pest insects and to maintain an abundance of pollinator insects to ensure the pollination of fruiting trees. A sequence of flowering plants throughout the season can also be used to feed honeybees for crops of honey and beeswax. (See Figure 10.3.)

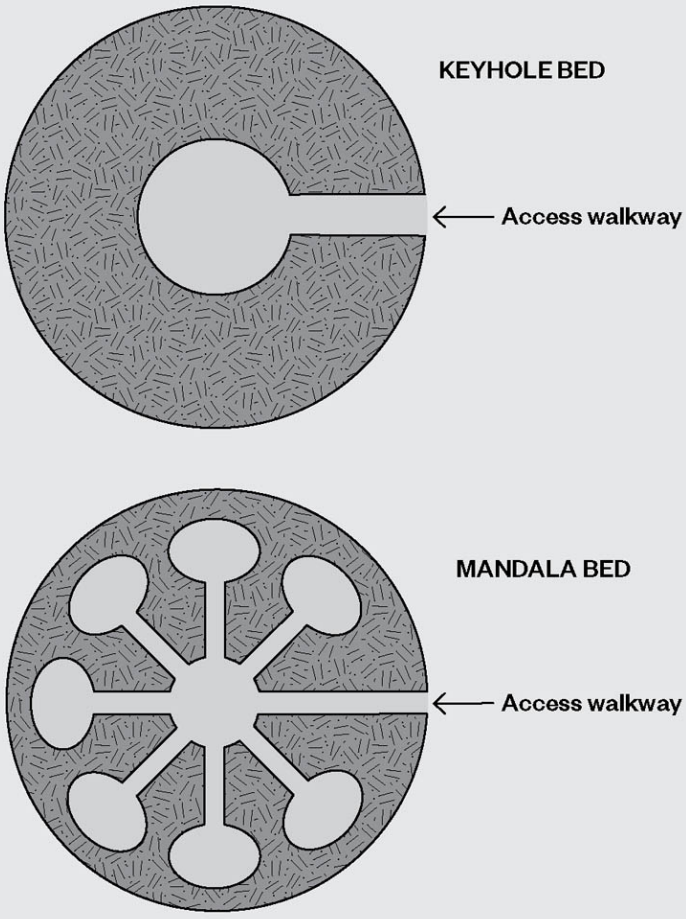
As a sample, the black walnut guild is illustrated opposite. Black walnut is a unique plant in that it emits the natural herbicide juglone, so all plants in the guild must be tolerant of juglone.

The concept of maximizing edges between two plant types is also maximized in permaculture and can greatly ease harvest by human power. For example, keyhole garden beds or mandala designs are used to provide easy access to all parts of a garden bed or guild.

Keyhole and Mandala Beds

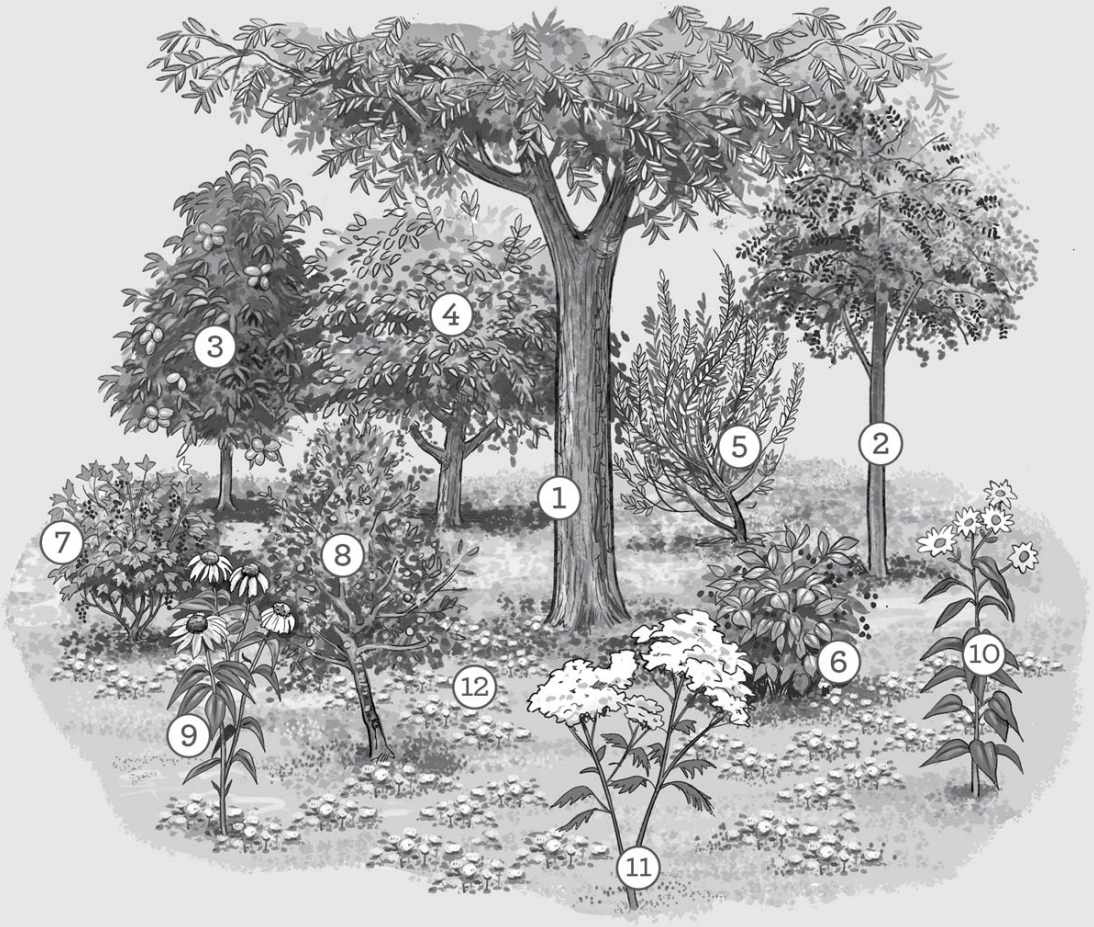
In permaculture, the production of food per unit of land area is of extreme importance. Where food is largely harvested by hand, people may require pathways to access the crops, and these pathways seldom produce food. A design that provides the most access to the most crops with the least amount of pathway is thus advantageous.

Two such designs are keyhole beds, used for smaller beds, and mandala beds, using the same geometric pattern as a keyhole bed but repeated in a circular pattern for use in larger beds. These two patterns provide access to all points of the beds with minimal area taken up by pathways.



MEMBERS OF A BLACK WALNUT GUILD

This black walnut guild features the following layers:



TALL TREES

1. Black walnut, useful for edible nuts and eventually valuable for lumber

SMALLER TREES

2. Pawpaw, useful for its edible banana-like fruit; also a potential source of natural insecticide and cancer-

fighting agents; a primary larval food plant of the zebra swallowtail butterfly

3. Persimmon, useful for edible fruit and valuable dark black timber, similar to ebony
4. Mulberry, useful for edible fruit in late spring when few other fruits are productive

SHRUBS

5. Autumn olive, a nitrogen-fixer with edible berries in fall that are very high in lycopene
6. Currants for edible berries in summer; high in antioxidants
7. Elderberry for edible berries that are very high in immune-stimulating properties
8. Black raspberry, for edible fruit

HERBACEOUS PLANTS

9. Echinacea, an immune-stimulant and topical pain reliever; also for pollinators
10. Jerusalem artichoke, a source of late-season bloom for honeybees and wild pollinators; also edible tubers that are a low-calorie alternative to potatoes (also a root crop)

11. Bee balm (*Monarda fistulosa*) for fragrance, bees, and pollinators; also a tasty herb

GROUND COVER

12. White clover for nitrogen-fixation and weed suppression; also great food source for honeybees

The Land Institute

Also in the 1970s, a California State University scientist named Wes Jackson observed that for thousands of years agriculture has focused on monocultures of annual plants like wheat and corn. An agriculture based on annual plants requires the elimination of competing vegetation prior to planting the annual crops; for most of history, this involved the use of the plow. Our agriculture was also based mostly on monocultures, which certainly aided mechanical planting and harvesting of crops and allowed for the use of selective herbicides for weed control.

Benefits and Virtues

But Jackson took note that nature almost always farms with perennials, and always in polycultures. Perennials come back from an established root system every year, and thus do not

need annual tillage. Perennials have deep and expansive root systems and are much less vulnerable to drought than annual plants, and the permanent cover and deep roots hold soil and prevent erosion. They also reduce weed challenges, since established perennials often outcompete annual weeds that must establish from seed every year.

Polycultures have many advantages over monocultures. A polyculture may have legumes in the mix to provide biologically fixed nitrogen to the rest of the plants; some plants may have deep taproots to seek water from deep in the soil, while others may have fibrous roots that mine the topsoil for water. Some plants in the mixture could be cool-season plants, which photosynthesize in spring and fall, while warm-season plants take over in summer, making for a longer season of growth and more efficient use of sunlight than a field of either alone.

Polycultures also serve as a hedge against any single disease or insect pest that may attack the system, as most pests and diseases are specific to a small range of plants. Belowground, the entire system could be bound together in cooperation through a network of mycorrhizal fungi and associated microbes.

Jackson's Vision

Jackson envisioned a form of agriculture based on a polyculture of perennial grasses, legumes, and forbs similar to the tallgrass prairie, but there was one problem with this vision: Perennial grasses produce very little seed. A crop of

annual wheat, for example, might produce an average crop of 50 bushels an acre (around 3,000 pounds per acre, or 3,300 kg/ha). In comparison, a crop of intermediate wheatgrass, a perennial grass that is closely related to wheat, might produce a crop of 500 pounds of seed per acre (220 kg/ha).

But, Jackson wondered, is this an inherent trait of perennials, or something that could be overcome with careful breeding and selection? After all, the first wheat plants grown in the Middle East thousands of years ago did not produce anywhere near 50 bushels an acre. It was only through centuries of selection and breeding that our current wheat varieties reached this level of productivity. Few plant geneticists had ever even tried to do anything similar with perennial grasses; perennial grasses were bred only for pasture production. Why not be the first? thought Jackson.

He moved back to his native Kansas, purchased a small tract of land near Salina, cofounded the research organization he called the Land Institute, and began to breed and select prairie plants for seed production. He also hybridized annual plants with related perennials, such as annual wheat with the related perennial wheatgrass, and annual grain sorghum with the related perennial johnsongrass.

Jackson has achieved considerable success, and the Land Institute has released a perennial wheat relative called Kernza that produces grain that can be utilized similarly to wheat. Kernza in its current state yields nowhere close to the top varieties of annual wheat, but it represents a major milestone in the development of perennial grains.

Like its intermediate wheatgrass parents, it is also an excellent forage plant. It can be planted in a combination with

a perennial legume, such as alfalfa or red clover, to provide nitrogen to the stand. After grain harvest, the Kernza straw (with intermingled alfalfa or clover) can be made into a moderate quality hay, with better feed value than wheat straw. The plants then regrow after harvest for an excellent yield of high-quality pasture in the fall, when the native grass pastures of the area have gone dormant and lost their pasture quality.

Kernza is not the final destination of perennial grain breeding but rather the first one developed for commercial use. Other perennialization projects involve perennial sunflowers for an oilseed; perennial legumes, like sainfoin, for a high-protein seed; perennial rice; and many others.

Jackson recently retired from his role as president at the Land Institute, but his work and vision continue there.

What a Wonderful World It Could Be

In Chapter 1, we discussed how agriculture as it has been practiced over the last 7,000 years has radically altered the world's landscape, and mostly for the worse. Agriculture that destroys soil and ecosystems is not a recent invention; it has been that way since before anyone put pen to paper to record history. I would actually argue that agriculture as it is practiced now is, in many ways, less destructive to soil than at any time in the last several thousand years. But that does not

mean our current form of agriculture is something we should be satisfied with—far from it.

We have a long, long way to go to achieve the form of agriculture that builds our soils to where they need to be for the future of this planet, or at least for the future of the human race on this planet. But we do not lack the tools or the knowledge to make these changes. Though we know little about soil compared to what we will someday know, it is a fact that if we simply implement the practices we currently know about rebuilding soil, we can quite literally change the face of the planet—and change it for the better. Just imagine if . . .

All the world's cropland is farmed without soil-destructive tillage and is protected by cover crops in between the primary crops, preventing soil erosion, encouraging the infiltration of rainfall into the soil, and slowing runoff. The cover crops pump life-giving root exudates into the soil to feed the trillion-strong army of underground microbes on every acre. The microbes enhance the yield and improve the nutritional quality of the crop while also adding vital organic matter to the soil each and every year for the promise of an even better harvest in years to come.

The cover crops nourish the belowground "livestock" (soil microbes) and provide an abundance of herbage that is harvested by grazing livestock and wildlife ranging from insects to elephants. The decaying residue, of both cover crops and primary crops, combines to nourish soil fungi, the spores of which become airborne to trigger much-needed gentle rains throughout the growing season. Blooming cover crops attract

butterflies and bees and also provide airborne pollen to help the fungal spores trigger gentle summer rains.

Organic matter begins to rise, globally, instead of continuing its 7,000-year period of decline in the world's cropland. The soil begins absorbing rainfall instead of allowing it to run off. It holds moisture for long periods of time, and the roots of crops can reach deeply and drink from the depths of the soil profile. Both famine-inducing droughts and destructive, deadly floods are a thing of the past.

The rich microbial life in the soil transfers both mineral nutrients and prebiotic compounds to plants—substances that impart a healthfulness to our food that has long been missing from our food supply. Cancer, heart disease, and diabetes no longer end lives before their time.

The world's pastures and rangelands are grazed in a manner that optimizes photosynthesis on every acre, allowing the forage to grow deeper roots, pump additional root exudates into the soil, sequester extra soil organic matter, and produce severalfold more herbage than it currently does. This additional herbage provides an abundance of feed for livestock, just as it creates a rich habitat for grassland wildlife. The world becomes a virtual Serengeti, a breathtaking sight of natural abundance. (See Figure 14.1.)

Meat from these animals—rich in essential fatty acids, iron, zinc, and fat-soluble vitamins—provides essential protein for a population starved for critical amino acids. The brain-nourishing substances in this meat allow full intellectual

development of the world's previously malnourished populations, giving them a chance to rise above poverty, hopelessness, and warfare.

Large swaths of cropland are converted to productive pastures, diverse forests, and even more diverse savannas of food-producing trees that provide shade to the livestock pasturing the grasses, forbs, and legumes underneath. These systems are not nature preserves; they are working agricultural lands that provide for people while simultaneously healing the planet, and yet they harbor more wildlife and biodiversity than the wild lands that were previously destroyed to make room for the crops.

The soil underneath the plants absorbs progressively more carbon out of the atmosphere each and every year, replacing it with clean, fresh oxygen. The deep, perennial roots create spongelike soil that absorbs and holds every rainfall, slowly releasing clean water to springs and streams.

The hypoxic zones at the mouths of rivers no longer exist, and shrimp and shellfish are once again abundant. Ocean farms of kelp and other seaweed harbor wild fish populations even greater than those that existed hundreds of years ago, and there is a surplus of fish that can be harvested.

The soils contain so much carbon taken out of the atmosphere that climate change fears are nothing but a distant memory. The water cycle is stable and frequent, and gentle rain is the norm rather than the exception. Droughts are no more. Floods

are just old memories, the stuff of stories told to children by their grandparents.

War is also a distant memory because food, clean water, and energy are so abundant that there is no need to fight over them. Famine is obviously no longer a concern, as food is plentiful. Pestilence is not a concern, as the highly nutritious food people consume stimulates our immune system to the point where it shrugs off disease and fights off cancers. Our diets are so rich in nutrition that we feel satisfied with fewer calories; we are no longer simultaneously obese and malnourished, and good health abounds in every part of the world.

The Four Horsemen of the Apocalypse have left the planet.

CONCLUSION

Together We All Must Write the Happy Ending

But the story only ends this way if we take action and put the knowledge we already have into practice. We are not currently doing that. Worldwide, only about 11 percent of the world's cropland is farmed without tillage, and less than 5 percent has cover crops growing on it between primary crops. Only a small fraction of the world's rangeland and pastures are grazed in

any form of rotational grazing, let alone an adaptive multipaddock system. We still destroy far more areas of forests and grasslands than we plant every year.

Will we take the actions necessary for a happy ending for the human race, or will we continue business as usual and slowly destroy our planet? A Chinese proverb says that a journey of a thousand miles begins with a single step. When an individual farmer or rancher or gardener takes a single step, we are well on our way on the thousand-mile journey to save our planet—one field, one pasture, one garden at a time. May you take that step on your own little piece of the planet.

◆◆◆

Thank you for reading this book.

I hope you found reading it as inspirational as writing it was for me, and that the information contained in it brings you joy and prosperity.

ACKNOWLEDGMENTS

No one pops out of the womb knowing anything. Everything we know is a result of our environment, primarily the people with whom we interact. I have been quite blessed to be able to interact with a multitude of wonderful, intelligent, and innovative people throughout my life.

Of course, my parents formed my first experiences, with my mother reading to me and teaching me to read at an early age. I was privileged to have grown up on a diverse and (for the time) innovative farm with my father and both grandfathers.

I was privileged to have had a teacher that changed my life. Due to constant misbehavior, I spent my first few years of school in, basically, some form of punishment or another, and my mother dreaded parent-teacher conferences.

Then my third-grade teacher, Mae Adams, realized that the root cause of my misbehavior was what they now call ADHD. Instead of recommending that my parents put me on some mind-numbing drug, she gave me a present of an empty three-ring notebook, paper, scissors, a roll of Scotch tape, and a big stack of nature and *National Geographic* magazines. She then asked me to make her a book about wild animals, because I was fascinated with them. From that moment on, I loved school and became a model student instead of a future inmate!

Later, I was privileged to major in agriculture at a fine land grant institution in the center of our country and to learn from some great agricultural minds. In college I was also privileged

to live in a fraternity of agriculture majors, and our late-night dorm room conversations gave me insight into how different farms overcame different challenges.

Then I was privileged to be offered a position as a graduate research assistant by Dr. Clenton Owensby so I could afford to attend graduate school, which allowed my mind to develop in ways I never knew were possible. After grad school, I was privileged to be offered a teaching position at Cloud County Community College by an administrator named Stanton Gartin, a wonderful mentor who would later become the best man in my wedding. I learned far more from my students than I ever taught them, and I remain in contact with many of those students to this day; three of them stood up with me in my wedding, next to Stanton.

When I entered private industry, many people influenced my development, including Bob Schoper and Jeff Ochumpaugh, who were among my early supervisors. When I bought my own farm, I was privileged to have my father-in-law, Dean Sothers, alive at the time, so he could temper my hare-brained ideas into a version that might work in the real world. He patiently helped me implement the ones that passed his screening so I could put my schemes to the test.

I was privileged to have great neighbors like Shane Langston, who helped me when I desperately needed it, no matter what form of help, what time of day, or how inconvenient it might be. I was privileged to become associated with the Kansas Graziers Association and Dan and Mary Howell and to meet all sorts of like-minded people with whom to share ideas.

And I have been privileged to work most recently for Keith and Brian Berns of Green Cover Seed, who have been exceptionally supportive of me on multiple levels. I don't know what I would have done if I had to work for anyone else during the trials of the past few years.

Anyone who is anyone in the field of soil regeneration seems to be personally known by the Berns brothers. Through Green Cover Seed I met many of the people profiled in this book, as well as so many other great minds from whom I learned so much.

In short, very little of this book erupted spontaneously out of the neurons in my pea brain. This book came about because I have led a life of privilege.

DIGGING DEEPER

There are many other excellent books on the topics covered in these pages. To receive my full list of "Essential Books on Soil Survival," please contact me at dale@greencoverseed.com.

For Further Reference

Learn more about projects, organizations, and research described in this book with these resources.

Al Baydha project ("Greening a Desert," page 64):
https://regenerativeresources.co

Blue Nest Beef ("This Beef Is for the Birds!", page 290):
bluenestbeef.com

Cactus Feeders ("Pastures Replace Feedlots," page 284):
www.cactusfeeders.com

Exapta Solutions, Inc., "No-till Seeding Explained" (DVD):
exapta.com

Centre for No-Till Agriculture (Kofi Boa, "Small-Scale No-Till in West Africa," page 216): centrefornotill.org

Green Cover Seed ("Design Your Own Cover Crop Blend," page 246): greencover.com

GreenWave (“Ocean Farming,” page 162): www.greenwave.org

Land Institute, The (“The Land Institute,” page 336): https://landinstitute.org/

Las Damas Ranch (“Restoring Desert Rangeland,” page 294): understandingag.com/case_studies/las-damas-ranch-case-study

Lloyd Murdock, A. D. Karathanasis, Chris Matocha, John Grove, Dottie Call, “Remediation of the Fragipan Using Annual Ryegrass,” University of Kentucky College of Agriculture, Food and Environment Cooperative Extension Service (2020).

R. B. Jackson, K. Lajtha, S. E. Crow, G. Hugelius, M. G. Kramer, G. Pineiro, “The Ecology of Soil Carbon: Pools, Vulnerabilities, and Biotic and Abiotic Controls,” *Annual Review of Ecology, Evolution and Systematics* Vol 48: 419-445 (2017).

Regenerative Agriculture Alliance (Reginaldo Haslett-Marroquin, “Returning Chickens to their Roots,” page 308): www.regenagalliance.org

Recommended Reading

Here are the bedrock volumes mentioned in this book.

Hensel, Julius. *Bread from Stones* (Acres USA, 1991)

Montgomery, David. *Dirt: The Erosion of Civilizations* (University of California Press, 2012)

Montgomery, David. *Growing a Revolution: Bringing Our Soil Back to Life* (W. W. Norton & Co., 2018)

Holzer, Sepp. *Sepp Holzer's Permaculture: A Practical Guide to Small-Scale, Integrative Farming and Gardening* (Chelsea Green Publishing, 2011)

Smith, J. Russell. *Tree Crops: A Permanent Agriculture* (lulu.com, 2015)

Stout, Ruth, and Richard Clemence. *The Ruth Stout No-Work Garden Book: Secrets of the Famous Year-Round Mulch Method* (Rodale Press, 1979) and other titles

Yeomans, P. A., and Ken B. Yeomans. *Water for Every Farm* (Second Back Row Press, 1981)

GLOSSARY

acid rain. Rain with an unnatural level of acidity due to pollution by nitric and sulfuric acid

active acidity. The portion of soil acidity that is found in the soil solution and can be measured

aerenchyma. A spongy, porous tissue found in the roots of some plants, designed for conducting oxygen to roots in low-oxygen soils

aggregate. A cluster of primary soil particles (sand, silt, clay) glued together with biologically derived glues

agroforestry. An agricultural system in which trees and herbaceous crops are both grown together in the same field

black layer. A dark-colored barrier formed within a kernel of corn upon maturity that seals the kernel contents from microbial attack

broadbase terrace. An earthen berm for control of soil erosion, with a gentle slope that allows it to be crossed with farm machinery so it can be cropped

buffer pH. A measure of the resistance of a soil to change in pH

cation. An atomic particle with a positive electrical charge

cation exchange. The uptake by plants of positively charged mineral nutrients from soil surfaces in exchange for hydrogen ions

cation exchange capacity. The ability of a soil to hold positively charged mineral nutrients and provide them to plants

check dams. Small, porous dams to slow the flow in a stream but not hold water for long periods of time

chelate. A mineral held in combination with an organic molecule that retains the mineral in a plant-available form

chitin. A substance composed of a protein-sugar combination that makes up the shells of crustaceans and the cell walls of fungi

diffusion. A gradual movement of a substance from areas of high concentration to areas of low concentration

divalent. An electrically charged particle with two electrical charges

ectomycorrhizal fungi. A type of fungi that colonizes plant roots in a mutually beneficial relationship, but does not physically penetrate the cells of the plant root

endomycorrhizal fungi. A type of fungi that colonizes plant roots in a mutually beneficial relationship

energy chain. In reference to plant/soil relationships, the flow of energy from sunlight to plants to soil microbes

flocculate. The clumping together of individual soil particles into large clusters of many soil particles

fragipan. A dense layer of soil that is chemically cemented

fredge. A line of trees placed to capture flood debris on flood plains

fulvic acid. A component of soil organic matter, produced by the decay of organic materials, with a very high capacity to hold and retain soil moisture and mineral nutrients in plant-available form. Fulvic acid is of lower molecular weight than the similar humic acid.

fungal spores. The reproductive structures of fungi, comparable to seeds

geologic parent material. The rock particles that provide the raw material for soil formation

glomalin. A sticky substance produced by mycorrhizal fungi that glues soil particles together into larger clumps

guild. A designed community of plants in which the plants are placed and selected to provide benefits to neighboring plants, resulting in a high level of community productivity

heavy metal contamination. An increased level in soil of toxic metals, such as lead and cadmium

Hügelkultur. A system in which large pieces of woody material are placed in the soil to slowly decay into spongy material with a high ability to retain soil moisture

humic acid. A component of soil organic matter, produced by the decay of organic materials, with a very high capacity to hold and retain soil moisture and mineral nutrients in plant-available form. Humic acid is of a higher molecular weight than the similar fulvic acid.

humus. The final product of the decay of plant residues, animal manures, and animal bodies in the soil, with a very high capacity to hold and retain plant nutrients and soil moisture, often used interchangeably with the term *organic matter*

hygroscopic. Possessing the ability to attract water vapor from the air

ions. Atomic particles with an electrical charge

Keyline landforming. A system of sculpting land surfaces to retain water on the landscape for an extended time

lithotroph. An organism that can derive nutrition from digesting rock particles, liberating mineral nutrients from rocks

mass flow. The flow of mineral nutrients dissolved in water toward plant roots as a consequence of the plant uptake of water

methanotrophs. Organisms that consume and derive energy from methane

microbial polysaccharide. A sugary substance produced by microbes, which usually functions to form a protective layer around the microbes to prevent moisture loss

mineral chain. In soil, the flow of mineral nutrients from rocks to microbes to plant roots

mucigel. A gelatinous substance, formed on the surface of plant roots, with a very high capacity to absorb and retain soil moisture

mycorrhizal fungi. A fungus that lives partially within plant roots and aids plants in the uptake of water and mineral nutrients, in exchange for sugar from the plant

net and pan. A formation of earthen berms that run in perpendicular lines to each other, slightly downhill. Their intersection forms a basin that retains rainfall, which would otherwise run off the soil surface.

nodulation. The formation on plant roots of structures filled with bacteria that convert atmospheric nitrogen into forms of nitrogen available for plant nutrition

osmotic potential. The ability of a substance to attract water to itself

pathogen. An organism that causes disease

pH. A measure of acidity, the concentration of hydrogen ions

pharmaceuticals. Medicinal drugs

photorespiration. A process occurring in some plants in which high temperatures cause a malfunction in photosynthesis and a reduction in plant productivity

pleached fence. A fence formed by the weaving together of live trees into an interlocked living and growing fence

reserve acidity. Hydrogen ions located on the surface of soil particles that can move quickly into the soil solution to become active acidity

respiration. The consumption and oxidation of energy containing substances by living organisms

rhizophagy. A process in which plant roots consume microbes and pull mineral nutrients from them

rhizosphere. The portion of soil immediately surrounding plant roots, and the layer of soil that is most biologically active

residual acidity. The hydrogen ions located within soil particles that are not active in the soil solution but move into the soil solution if the acidity in the soil solution is neutralized

saline soil. A soil with levels of salt that are high enough to prevent plant roots from obtaining water

saline-sodic soil. A soil that has excessive levels of both salt and sodium

saprophytes. Organisms that derive nourishment from the consumption of dead plant or animal tissues

saprophytic. Refers to an organism that feeds upon dead tissue

siderophores. Compounds produced by microbes that enhance the availability of iron to plants

silvopasture. A combination of livestock pasture and trees, in which the trees produce a crop of some value such as timber, forage, or fruit

sodic soil. A soil in which the sodium content is in excess. The consequence is that the soil structure condenses into a solid material with very little pore space.

strigolactone. A chemical compound exuded by plant roots that triggers colonization of plant roots via mycorrhizal fungi

swale. A combination of a long, linear earthen berm and an excavation, placed on the same elevation, to capture and retain rainwater that would otherwise run off the landscape

terraces. An earthen berm designed to slow the downhill flow of water and prevent soil erosion

tied up. In reference to plant nutrients, becoming rendered unavailable to plants

tiller. A newly formed stem at the base of a grass plant

vertical mulch. A narrow trench filled with coarse material, such as straw and manure, designed to improve the infiltration of rainfall into the soil

water spreader. A structure composed of earth or stone, placed in a stream perpendicular to the direction of water flow, and designed to move water out of the stream onto adjacent lands

worm cast. The feces of an earthworm, a highly desirable growing medium for plants

METRIC CONVERSION CHARTS

Weight

TO CONVERT	TO	MULTIPLY
ounces	grams	ounces by 28.35
pounds	grams	pounds by 453.5
pounds	kilograms	pounds by 0.45

Length

TO CONVERT	TO	MULTIPLY
inches	millimeters	inches by 25.4
inches	centimeters	inches by 2.54
inches	meters	inches by 0.0254
feet	meters	feet by 0.3048
feet	kilometers	feet by 0.0003048
yards	centimeters	yards by 91.44
yards	meters	yards by 0.9144

Length

yards	kilometers	yards by 0.0009144
miles	meters	miles by 1,609.344
miles	kilometers	miles by 1.609344

Area

1 acre = 0.4 hectares
1 square mile = 2.6 square kilometers
1 hectare, or 10,000 square meters = 2.4711 acres
1 square kilometer = 0.3861 square miles

Temperature Range

FAHRENHEIT TO CENTIGRADE EQUIVALENTS, BY 10S	CENTIGRADE TO FAHRENHEIT EQUIVALENTS, BY 10S
–10°F = –23°C	–20°C = –4°F
0°F = –17.7°C	–10°C = 14°F
10°F = –12°C	0°C = 32°F
20°F = –6.6°C	10°C = 50°F
30°F = –1°C	20°C = 68°F

Temperature Range

32°F = 0°C	30°C = 86°F
40°F = 14.4°C	40°C = 104°F
50°F = 10°C	50°C = 122°F
60°F = 15.5°C	
70°F = 21°C	
80°F = 27°C	
90°F = 32°C	
100°F = 38°C	
110°F = 43°C	
120°F = 49°C	

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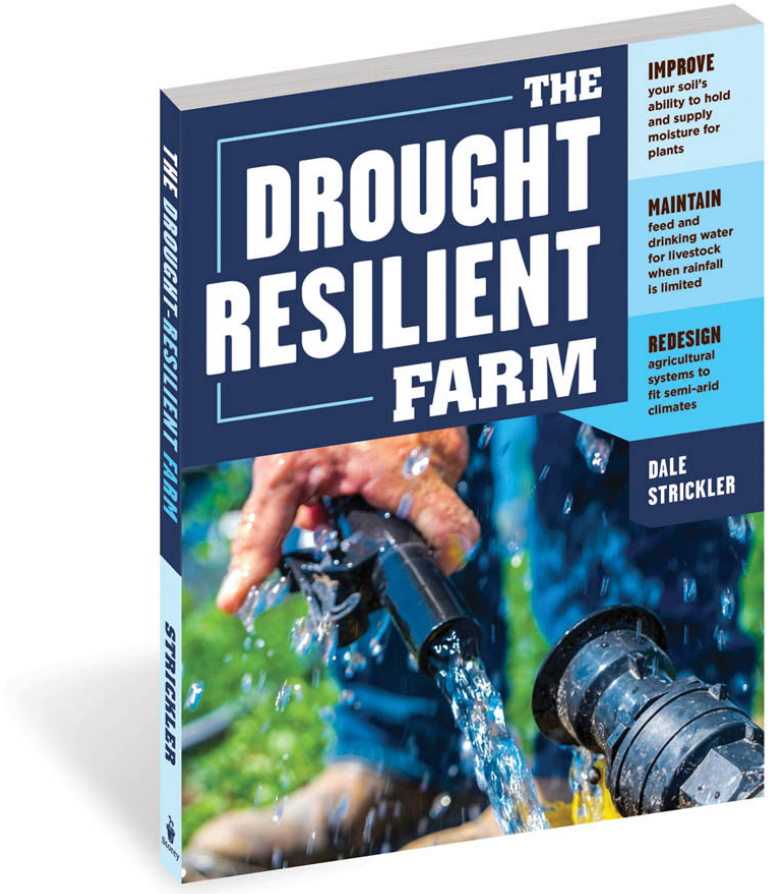

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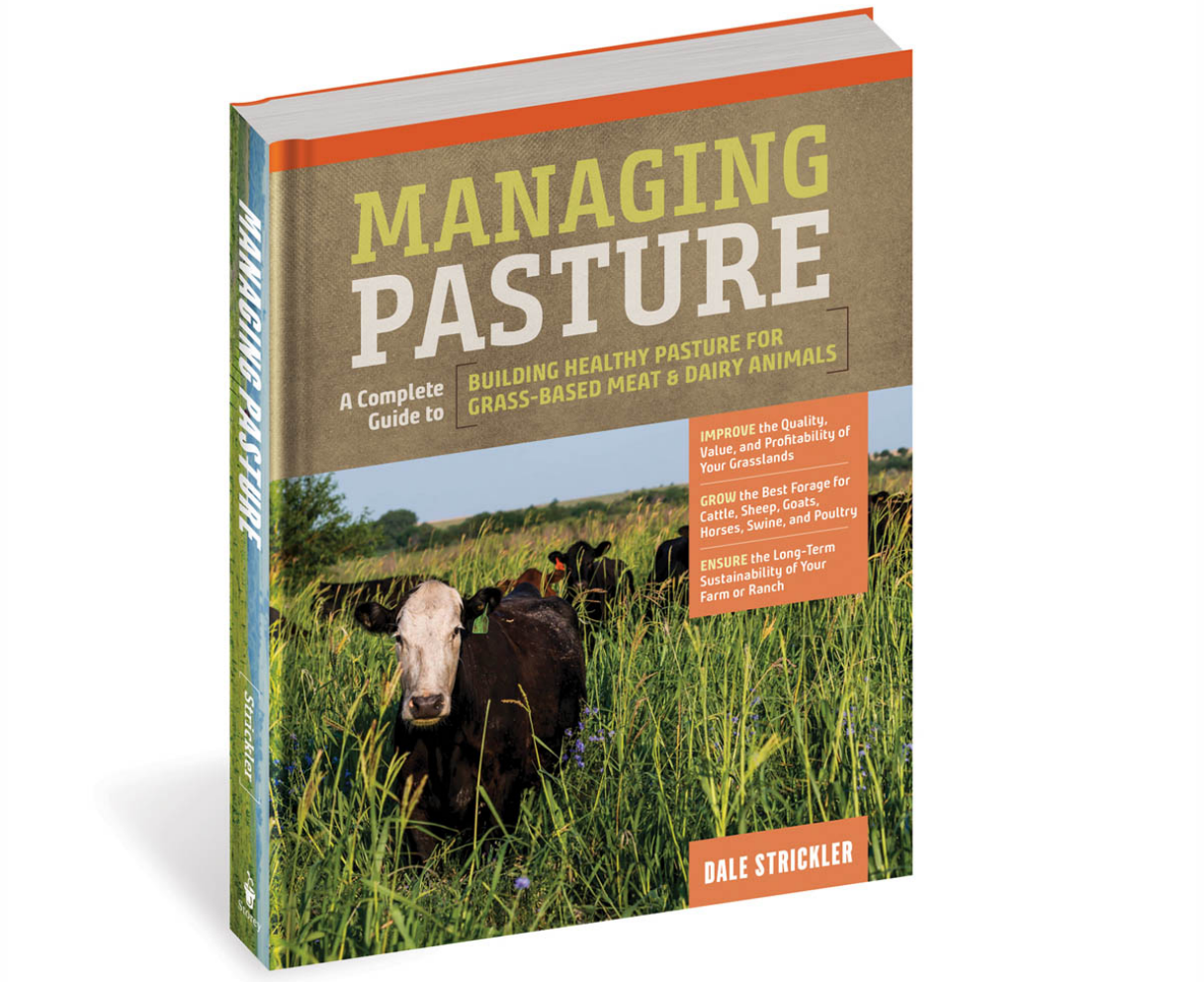
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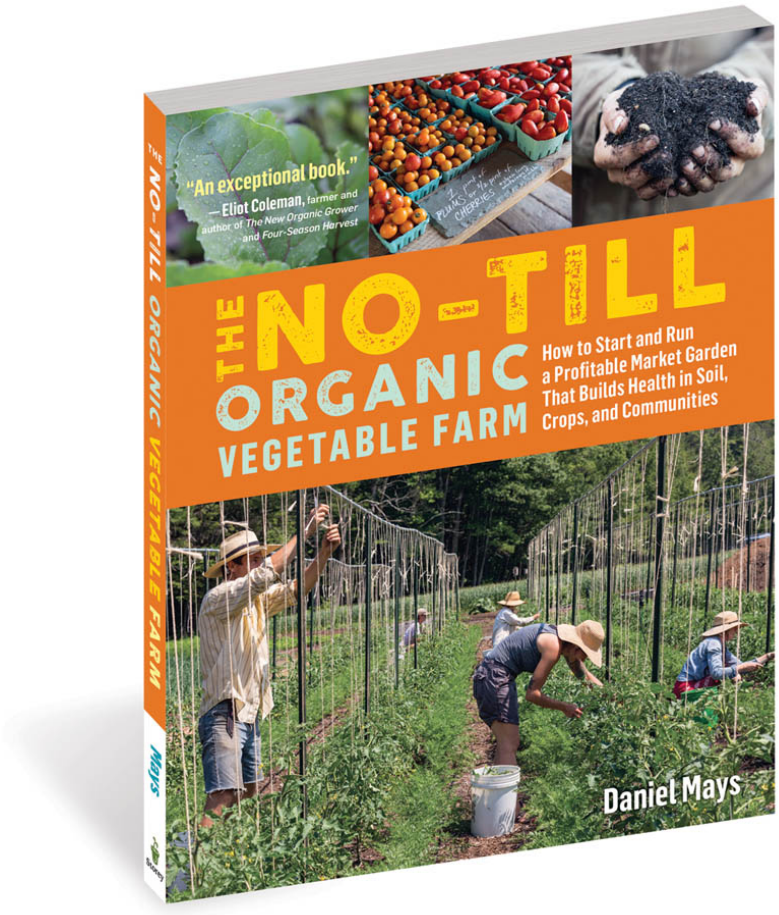
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